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A Multi-Proxy Paleoecological Reconstruction of Holocene Climate, Vegetation, Fire and Human Activity in Jamaica, West Indies

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A MULTI-PROXY PALEOECOLOGICAL RECONSTRUCTION OF HOLOCENE CLIMATE, VEGETATION, FIRE AND HUMAN ACTIVITY IN JAMAICA, WEST INDIES

By

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An Abstract of the Thesis Presented
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Jamaica is located in the Caribbean biodiversity hotspot and has a rich flora and fauna, most notably characterized by exceptional levels of plant endemism. These natural resources are imperiled by climate change and increasing anthropogenic pressures, therefore highlighting the importance of implementing effective conservation programs to mitigate ecosystem degradation. Paleoecological studies that investigate the diversity and distributions of organisms and their habitats over millennial timescales provide critical long-term spatial and temporal context for the assessment of contemporary environmental problems. Lake sediments are a highly useful archive for the study of prehistoric climate and ecological changes, as biological, chemical and geophysical remnants of ancient environments sequentially accumulate on lake bottoms over time, thus providing an integrated record of past environmental variability. Jamaica's prehistory is not well known from both an ecological and human perspective, therefore providing a special opportunity to apply paleoecological methods to the investigation of the past environments of an understudied area. This thesis investigates the paleoecological history of Jamaica within the context of millennial-scale relationships among humans, climate and the environment throughout

the Holocene. Chapter 1 provides a review of the utility of lake sediment coring and paleoecological data for reconstructing past environments and climates, paleoenvironmental research in low-latitude environments and relationships among climate, biodiversity, and human populations in the tropics, and the history of climate, vegetation, fire and human activities in the Caribbean Basin as illuminated by prior paleoecological research. In sum, Chapter 1 provides a broader spatial context for understanding the timing and magnitude of paleoecological changes in Jamaica and allows for the framing of past changes in climate and human activities in Jamaica within a regional model of prehistoric environmental variability. Chapter 2 examines the paleoenvironments, paleoclimates and prehistoric human populations of Jamaica. A novel multi-proxy paleoecological reconstruction that records prehistoric changes in climate, fire, vegetation and human activities in Jamaica from the mid-Holocene to modern times is presented. Four successive waves of human colonization were documented in the lake sedimentary record, including the arrival of the Ostionoid peoples, the first group to colonize the island. Initial colonization of the island was coeval with a period of increased fire regimes and large vegetation shifts, including the loss of a swamp mangrove-fern community which failed to re-establish after disturbance. Subsequent waves of colonization by the Meillacan peoples, Taino, and Europeans were associated with increases in fire activity above background levels. The paleoecological record revealed that the Maya Drought (AD 750-AD 950) was represented by arid conditions in Jamaica, while the Medieval Warm Period (AD 800-AD 1300) and Little Ice Age (AD 1400-AD 1800) were represented by wet and dry climates respectively.

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CHAPTER 1

PALEOECOLOGICAL PERSPECTIVES ON CLIMATE AND ENVIRONMENTAL CHANGES IN THE TROPICAL CARIBBEAN BASIN

Article scope and objectives

This review primarily considers the: 1) application of lake sediment coring methods and sedimentary proxy data to paleoecological and paleoclimatic reconstructions, 2) status of tropical paleoenvironmental research and linkages between biodiversity, climate, economy, and prehistoric human activities in low-latitude areas, and 3) the history of vegetation, climate, fire and human activities in the Caribbean region as illuminated by existing paleoecological archives.

Multi-proxy paleoecological approaches: applications and insights

The analysis of organic and inorganic proxies found in lake sediments is a highly useful tool for reconstructing past climate and environmental variability beyond the scope of temporally-limited instrumental records. For example, biotic and abiotic proxies from lake sediments collected from sites distributed across the circumpolar North indicate that Arctic lake ecosystems are experiencing physical and ecological regime shifts that are unprecedented over centuries to millennia (Smol et al., 2005; Smol and Douglas, 2007); and coastal lake sediment records have yielded millennial-scale reconstructions of hurricane frequency and intensity in the northern Gulf of Mexico (Liu and Fearn, 2000; Lambert et al., 2008). Furthermore, data from lake sediments have been used to investigate past abrupt climate events in order to better

contextualize modern rates of temperature change and the ecological consequences of recent anthropogenic warming (Stivrins et al., 2016; Ammann et al., 2000; Birks and Birks, 2008).

Lake sediments contain a broad diversity of biological and biogeochemical proxies that provide detailed information about different aspects of past changing environments. Environmental proxies commonly used in paleoecological and paleoclimatological research include: pollen (Seppä and Bennett, 2003), chironomids (Brooks, 2006), diatoms (Bigler and Hall, 2002), stable isotopes (Leng and Marshall, 2004), percent loss-on-ignition (Heiri et al., 2001), charcoal (Ali et al., 2009), and magnetic susceptibility (Thompson et al., 1975), among several others. Environmental materials from the surrounding catchment, such as pollen and charcoal, are either aerially deposited or washed into lakes, and accumulate in a sequential manner on the lake bottom over time. These lacustrine sedimentary sequences frequently provide high-resolution proxy records, which may be sampled at decadal or sub-decadal time intervals—and in the case of varved lake deposits, provide annual to seasonal resolution (Zolitschka et al., 2015).

The simultaneous use of multiple proxies in single studies provides several lines of evidence that can be independently validated for accuracy, and strengthens the overall conclusions made from such studies as researchers obtain a more comprehensive understanding of the paleoenvironmental changes being assessed (Birks and Birks, 2006; Lotter, 2003). The relatively recent emergence of multi-proxy analyses in paleolimnological research in conjunction with the development of novel proxies, such as environmental DNA (eDNA; Parducci et al., 2017, 2013) and a wide range of molecular organic markers; such as long-chain alkenones (LCAs), plant-derived n-alkanes, levoglucosan and polycyclic aromatic hydrocarbons (PAHs) (Castañeda and Schouten, 2011; Elias et al., 2001; Denis et al., 2012), ensure the advancement of

paleoclimatology and paleoecology as researchers now possess the tools to rigorously address previously unanswerable questions.

Most of what we currently know about millennial-scale global climate change is based on ice core records collected from polar environments (Johnsen et al., 2001; Masson et al., 2000), and paleoecological reconstructions conducted in high-latitude regions such as North America and Europe (Jones and Mann, 2004; Schoonmaker and Foster, 1991). Despite the existence of tropical paleoclimate reconstructions based on corals (Gagan et al., 2000), marine sediment cores (Haug et al., 2001; Maslin and Burns, 2000), speleothems (Lachniet et al., 2004; Yadava and Ramesh, 2005), and ice cores retrieved from high-altitude ice fields (Thompson et al., 2000), low-latitude paleoclimate reconstructions remain relatively sparse compared to high-latitude regions, therefore leaving a persistent research gap in our understanding of long-term climate variability in the tropics.

The tropics: geography, climate, biodiversity and human history

The tropics are geographically defined as the regions of Earth that lie between the Tropic of Cancer (23.5°N) and the Tropic of Capricorn (23.5°S). Unlike the temperate zone, the tropics experience minimal seasonal variation in temperature, with yearly average temperatures at sea level rarely falling below 18 °C (64 °F). However, tropical precipitation patterns exhibit high seasonality due to the strong influence of the Intertropical Convergence Zone (ITCZ) on regional rainfall. The ITCZ is a horizontal band of low atmospheric pressure located roughly at the equator. It is characterized by high convection, cloudiness and thunderstorms. The ITCZ migrates northward during boreal summer (austral winter, June to August) and southward during austral summer (boreal winter, November to January) in response to latitudinal variation in solar

insolation. Consequently, tropical areas experience a seasonal cycle of precipitation maxima that is tightly linked to the annual movement of the ITCZ (Osborne, 2000).

Tropical terrestrial ecosystems typically support diverse assemblages of plant and animal taxa, with particularly elevated levels of species richness and endemism (Myers, 1988; Mittermeier et al., 1998). In a seminal paper, Myers et al. (2000) investigated the global distribution of 'biodiversity hotspots'—regions that exhibit high levels of species endemism and experience acute habitat loss—and identified 25 hotspots that are the last remaining refuge for over 40% of all global plant species and more than a third of all global vertebrate species. Of the 25 identified biodiversity hotspots, tropical forests were present in 15, and virtually all tropical islands were located in a hotspot (Myers et al., 2000). The total area of the 25 biodiversity hotspots represents less than 2% of the Earth's terrestrial surface and has already experienced a greater than 85% reduction in primary vegetation (Myers et al., 2000). More than 1 billion people inhabit biodiversity hotspots, and these populations are increasing at a faster rate than the global average—1.8% per year in hotspots versus the global population growth rate, 1.3% per year (Cincotta et al., 2000). In addition to the risks posed by climate change (Corlett, 2012), tropical ecosystems will likely continue to be threatened by a broad range of potentially detrimental human activities—such as land conversion for agriculture (Laurance et al., 2014), road incursion (Laurance et al., 2009), over-hunting for bush meat and illegal trade (Harrison et al., 2016; Milner-Gulland et al., 2003), and urban expansion (Seto et al., 2012).

Climate change is projected to have a wide range of impacts on tropical ecosystems and human populations. The tropics are expected to develop no-analog climates by the year 2100, which may increase the probability of reorganization of tropical ecological communities. Furthermore, tropical species will face heightened extinction risk if they are unable to effectively

track their climate niches as they shift, or if their suitable climate conditions disappear altogether (Williams and Jackson, 2007; Williams et al., 2007). Tropical species may also be more vulnerable to future climate changes than their temperate counterparts due to their lower temperature tolerance and acclimation ability (Tewksbury et al., 2003; Deutsch et al., 2008). Climate-driven sea level rise poses a considerable threat to tropical biodiversity. Conservative estimates indicate that a 1-6 m increase in sea level would inundate large areas of land on tropical islands, resulting in significant habitat reduction and endangerment of up to hundreds of endemic species (Bellard et al., 2014; Menon et al., 2010; Wetzel et al., 2012). The issue of environmental migration has gained increasing attention in the literature, particularly with regards to the role of sea-level rise in the displacement of human populations in the tropical islands of the Pacific and Indian Oceans (Yamamoto and Esteban, 2017; Constable, 2017; Berchin et al., 2017). Additionally, future climate warming will likely increase tropical cyclone intensity which, in conjunction with projected sea-level rise and the risk of enhanced storm surges, poses a serious threat to ecosystems, human lives and infrastructure (Sobel et al., 2016; Walsh et al., 2016; Knutson et al., 2010; Grinsted et al., 2013).

The tropics were also the site of some of the world's most developed ancient civilizations, with complex societies that practiced large-scale agriculture, conducted long-distance trade, built immense urban centers, engaged in organized warfare against neighboring city states, and conceived mathematical and astronomical models for understanding both the natural and spiritual underpinnings of their cultural existence. These civilizations include, but are not limited to: the Classic Mayan Empire (AD 250- AD 900) which stretched from the Yucatan Peninsula in the north to the Guatemalan Highlands and northern Honduras in the south (Dunning and Beach, 2010; McNeil, 2012; Webster, 2000; Thompson, 1974), the Aztec Empire

(12th-early 16th centuries) which occupied vast tracts of land in central Mexico (Smith and Berdan, 1992; Santley, 1985; Werner, 1992; Isaac, 1983), and the Khmer Empire (9th- early 15th centuries) which covered much of modern-day Thailand, Cambodia, Laos and Vietnam (Hendrickson , 2010; Evans et al., 2007; Evans et al., 2013). Researchers from a broad array of academic disciplines have debated the underlying causes of societal collapse for these ancient tropical civilizations, with a longstanding focus on the extent to which climate and environmental changes are implicated as major drivers of past societal failures (Haug et al., 2003; Kennett et al., 2012; Medina-Elizalde and Rohling, 2012; Diamond et al., 2009; Turner and Sabloff, 2012; Buckley et al., 2010; Dunning et al., 2012).

The Caribbean: geography, biodiversity and climate

The Caribbean geographical area lies approximately between 10 to 27°N latitude and 57 to 87°W longitude. The region includes the islands of the Caribbean Sea, a large partially enclosed basin of the mid-western Atlantic Ocean, and is bordered in the west by the Gulf of Mexico and eastern Central American coastline, in the north by the Bahamian archipelago, in the east by the Lesser Antilles island arc, and in the south by the northern South American coastline. The Lesser Antillean islands extend from the US and British Virgin Islands in the north to Grenada and Trinidad and Tobago in the south. The Greater Antilles are located south of the Bahamian archipelago and include the comparatively larger islands of Cuba, Jamaica, Hispaniola, and Puerto Rico. Hispaniola is comprised of the nations of Haiti on its western end and the Dominican Republic on its eastern end. The mainland Central and South American countries of Belize, Guyana and Suriname are frequently considered to be part of the Caribbean region based on cultural and historical similarities, as well as strong political and economic ties.

For example, all three nations are members of the Caribbean Community (CARICOM), a multinational organization that aims to advance the development of its member states through economic collaboration, foreign policy cooperation, and the promotion of trade, among other activities (O'Brien, 2011).

The Caribbean is recognized as one of the world's biodiversity hotspots based on endemicity and species vulnerability due to habitat loss (Myers et al., 2000; Brooks et al., 2002; Mittermeier et al., 2004). European explorers recorded descriptions of the Caribbean's floral diversity as early as the 15th century, and the region has an extensive history of botanical collecting (Santiago-Valentin and Olmstead, 2004). Myers et al. (2000) estimated that the Caribbean has approximately 12,000 vascular plant species, of which more than 50% are endemic—that is, over 2% of global plant species. The Caribbean vertebrate fauna is also characterized by exceptional endemism with several extant taxonomic groups, including amphibians, reptiles and freshwater fishes, consisting almost entirely of species found nowhere else on the planet (Hedges, 1996).

Approximately 85% of non-flying Caribbean mammals have gone extinct since the late Pleistocene and as a consequence, the present-day mammalian fauna of the region is a depauperate remnant of a once diverse assemblage of species (Morgan and Woods, 1986; Dávalos and Turvey, 2012). Previous studies indicate that climate and sea-level changes during the late Pleistocene-Holocene transition likely had a major role in Caribbean vertebrate extinctions and range contractions (Dávalos and Russell, 2012; Pregill and Olson, 1981). However, radiocarbon-dated fossil evidence indicates that several now-extinct vertebrate taxa persisted well into the Holocene, which suggests that anthropogenic activities (e.g. overhunting, habitat destruction, and exotic species introductions) were an important driver of regional late

Quaternary species extinctions (Soto-Centeno and Steadman, 2015; Steadman et al., 2005; Steadman et al., 1984). Notable extinct vertebrate taxa that have received interest from researchers, as well as the non-scientific community, include the Jamaican flightless ibis (*Xenicibis xympithecus*) which scholars believe to have used its wings as club-like weapons (Longrich and Olson, 2011), and the Caribbean monk seal (*Monachus tropicalis*) which went extinct as recently as 1952 (McClenachan and Cooper, 2008).

The tourism and agricultural sectors are critical to Caribbean economies, in terms of both their contributions to regional gross domestic product and employment (Taylor et al., 2012; Pulwarty et al., 2010; Barker, 2012). This socioeconomic reality makes Caribbean populations particularly susceptible to the negative effects of projected climate changes, as the growth and sustainability of these industries are closely linked to climate variations (Uyarra et al., 2005; Scott et al., 2012; Lewsey et al., 2004). Modeling studies generally predict a 10-50% decrease in annual precipitation for the majority of the Caribbean by the approximate period 2070-2100, although the simulation results vary spatially (Campbell et al., 2011; Hall et al., 2013). Over a similar time period, a 2-3 °C temperature rise is projected for the entire Caribbean (Campbell et al., 2011; Hall et al., 2013). Furthermore, climate change and the resultant increase in North Atlantic sea surface temperatures may cause an increase in Atlantic hurricane intensity, which has significant consequences for individuals, property, infrastructure and ecosystems in the Caribbean (Elsner, 2006; Moore et al., 2017).

The Caribbean has a hot climate with average monthly temperatures in excess of 18 °C (Peel et al., 2007). The annual precipitation in the region exhibits a bimodal pattern, with an early rainfall season from May to July and a late rainfall season from August to November—the latter of which coincides with the Atlantic hurricane season, and has higher precipitation levels

(Taylor et al., 2002). Precipitation maxima in the Caribbean Basin coincide with northern displacement of the ITCZ during boreal summer (Hastenrath and Polzin, 2013). The ITCZ migrates latitudinally in response to differences in inter-hemispheric heat, with movement towards the warmer hemisphere and increased energy flux towards the colder hemisphere a stabilizing feature of the global climate system (Mantsis and Clement, 2009; Donohoe et al., 2013). Consequently, ITCZ migration can occur over several timescales—from seasonal (Wu et al., 2003) to millennial (Russell and Johnson, 2005)—and in response to different climate forcings, including variations in high-latitude ice extent (Chiang and Bitz, 2005; Chiang et al., 2003), and changes in the oceanic thermohaline circulation (Wu et al., 2008; Stouffer et al., 2006). Hodell et al. (1991) showed that Holocene wet and dry periods in the Caribbean can be explained by millennial-scale variation in solar insolation, where a more northerly ITCZ delivered increased precipitation to the region during periods with enhanced Northern Hemisphere summer insolation. Over shorter timescales, Caribbean precipitation is also influenced by the North Atlantic high pressure system (Giannini et al., 2000; Gamble et al., 2008), the El Niño–Southern Oscillation (Chen and Taylor, 2002; Jury et al., 2007), the Caribbean low-level jet (Cook and Vizy, 2010), and the Madden-Julian oscillation (Martin and Schumacher, 2011).

Several lake sediment cores have been collected previously from the Caribbean Basin, in order to investigate paleoclimatic and paleoenvironmental changes that occurred in the region. In the past, researchers have aimed to better understand the spatial and temporal variability of climate within the region, the primary drivers of landscape-level changes, and the role of extreme climate events in shaping the trajectories of various prehistoric societies. Lacustrine sediment-based proxies that are commonly used to address these broad areas of inquiry include pollen,

charcoal, and stable isotopes—however, novel proxies, such as *Sporormiella*, have the potential to provide valuable insights into the human and environmental histories of the Caribbean region.

Paleoecological proxies: stable oxygen isotopes, pollen, *Sporormiella* and charcoal

The source area for biological materials—such as pollen, charcoal and *Sporormiella* fungal spores—deposited into a lake varies depending on the specific environmental proxy being considered. Previous empirical and modeling studies have provided valuable insights into the relationships between the source area for various environmental indicators and lake size, which enables improved spatial interpretation of proxy records contained in lake sediment cores. For pollen preserved in lake sediments, the general relationship is that smaller lakes reflect local vegetation communities while larger lakes reflect broader-scale, regional vegetation communities (Davis, 2000). For example, the Prentice-Sugita model—which links pollen abundances in lake sediments to vegetation structure in the surrounding catchment—showed that pollen assemblages in forest hollows (radius, R = 2 m), small lakes (R = 50 m), and medium-sized lakes (R = 250 m) are representative of local vegetation from source areas of ~75 m, ~350 m, and ~750 m from the lake edge respectively, for a patchy landscape. The same model indicated that pollen assemblages in large lakes (R = 750 m) are unsuitable for reconstructing local plant communities as they tend to represent a homogenous regional vegetation signal, as opposed to capturing adequately the site-to-site variation present in small, heterogenous patches (Sugita, 1994). Among other factors, the amount of charcoal deposited into a lake during a fire event is a function of fire intensity and frequency, the distance of the fire from the basin, charcoal particle size, the material being burnt and wind speeds. Microscopic charcoal (< 50 μm) is generally dispersed over longer distances (1–100 km) than macroscopic charcoal (> 50 μm; < 1 km);

therefore, sedimentary microscopic charcoal records are a proxy for regional fire regimes while macroscopic charcoal records represent local fire regimes (Clark, 1988; Peters and Higuera, 2007). Modern calibration studies indicate that *Sporormiella* is dispersed over short distances (< 100 m), and thus, is a suitable proxy for local herbivore abundances or herbivore presence (Gill et al., 2013; Raper and Bush, 2009). Consequently, lake sediments record landscape changes over a broad range of spatial scales, and in conjunction with paleoclimate data, they represent a powerful tool for reconstructing environmental responses to climate variability through time.

$\delta^{18}O$ values measured from ostracod shells reflect the evaporation-precipitation (E/P) regime of shallow lakes; as the lighter oxygen isotope (^{16}O) preferentially evaporates during arid climatic periods, thus increasing the levels of the heavier isotope (^{18}O) in lake water. Ostracods incorporate oxygen into their calcite shells from their host lake water during growth; therefore, changes in the E/P balance of the lake are recorded by the isotopic composition of ostracod shells preserved in lake sediments (Hodell et al., 1991; 1995). For example, using $\delta^{18}O$ measurements from fossil ostracods and authigenic carbonate collected from high-altitude lakes, Schwalb et al. (1999) found that the mid- to late Holocene transition in the Chilean Altiplano was marked by a regionally coherent series of abrupt climate changes. Similarly, Lister et al. (1991) assessed fossil ostracod $\delta^{18}O$ values to reconstruct lake levels of the Lake Qinghai basin in China, and specifically, to investigate the role of late Quaternary monsoon variability in controlling the past climate and hydrology of the region. However, care should be exercised when inferring paleoclimatic patterns from ostracod records, as ostracod $\delta^{18}O$ values are affected not only by E/P changes, but are also influenced by the isotopic signature of rainfall in the catchment, lake mixing, and lake size—as well as species-specific differences in isotopic fractionation that arise

from interspecific variation in calcification rates and habitat use, among other factors (Leng and Marshall, 2004; Keatings et al., 2002; von Grafenstein et al., 1999).

Preserved pollen (Figure 1.1) identified taxonomically and quantified using a microscope indicates changes in the vegetation of a region over time (Bennett and Willis, 2002; Faegri et al., 1989). For example, a shift of pollen from moisture-adapted species to drought-tolerant species would indicate a transition from mesic to more arid climatic conditions (Hodell et al., 1991). Deforestation for agriculture is indicated by an abrupt decline in tree pollen and increases in pollen from crops (e.g. *Zea mays*, *Cucurbita*, and *Helianthus annuus*), grasses (*Poaceae*) and weedy species (e.g. *Asteraceae*, *Amaranthaceae*, and *Plantago*) (Sanford Jr and Horn, 2000; Dubois et al., 2018; Mcandrews, 1988). Fossil pollen data from Massachusetts, USA demonstrated that 18th and 19th century European settlement in New England was associated with a shift in forest composition from late successional species, such as sugar maple, hemlock and beech, to disturbance-tolerant species, such as white pine, red maple and birch (Fuller et al., 1998). Furthermore, fossil pollen data can be applied to the study of the distributional responses of plant species to past climate changes. For example, Davis and Shaw (2001) used fossil pollen data to illustrate the responses of North American tree species to climate changes at the end of the last glaciation—some taxa, such as spruce (*Picea*), shifted their entire range, while other taxa, such as oak (*Quercus*), continued to grow near glacial refugia, therefore highlighting that species respond individualistically to environmental changes based on underlying adaptations to different climate factors (e.g. temperature, rainfall, seasonality).

Sporormiella is a fungus that only inhabits herbivore dung and produces characteristic spores that remain identifiable in prehistoric sediments (Gill et al., 2013). Previous studies have showed that *Sporormiella* abundances are a reliable proxy for herbivore density and can be

interpreted within the contexts of both megafauna and historical livestock populations (Davis, 1987; Raczka et al., 2016). Raper and Bush (2009) demonstrated that *Sporormiella* spores preserved in lake sediments can be used to estimate past grazing intensity, and that within-lake *Sporormiella* abundances decline with increased distance from the shoreline—thus highlighting that *Sporormiella* concentrations in lake sediments are sensitive to lake level variations. Similarly, Wood et al. (2016) found that sedimentary *Sporormiella* concentrations closely tracked the recorded history of herbivore introductions and consequent vegetation shifts on Enderby Island, New Zealand. *Sporormiella* fungal spores are easily observed on microscope slides prepared for pollen analysis (Burney et al., 2003), and statistical analyses indicate that a count of 300-350 markers per slide (e.g. *Lycopodium* spores, or plastic or ceramic microspheres) is adequate for accurately estimating *Sporormiella* abundance (Etienne and Jouffroy-Bapicot, 2014).

Sharp increases in charcoal particles in sediment cores have been used to detect landscape burning associated with human arrival on islands (Burney, 1997; Burney and Burney, 2003). Charcoal abundances estimated from lake sediment records can illuminate the magnitude, frequency and variability of landscape burning over various spatial scales, in order to better understand human use of fire through time and relationships between fire, climate and vegetation (Iglesias et al. 2015). For example, charcoal paleorecords indicated that despite contemporary increases in anthropogenic burning associated with land clearance and agriculture in northeastern Cambodia monsoon forests, modern charcoal production is relatively very low within the context of the past 9,000 years, therefore calling into question the efficacy of fire suppression schemes currently used to manage the forests (Maxwell, 2004). Over a much longer timescale, analysis of charcoal in a marine sediment core from offshore southwestern Africa demonstrated that

grassland burning in southern Africa over the past 170,000 years was driven by shifts in the position of the ITCZ, which in turn was controlled by changes in the Earth's precessional cycles (Daniau et al., 2013).

Caribbean paleoenvironments and paleoclimates: insights from sedimentary records

Despite a recent surge of interest in using paleoecological data to inform contemporary ecosystem management and conservation (Nogué et al., 2017; Wingard et al., 2017; Spencer et al., 2017; Whitlock et al., 2017; Chambers et al., 2017; Cohen, 2017), the circum-Caribbean remains one of the least understood regions from a paleoecological perspective. Our current knowledge of millennial-scale linkages between Caribbean climate, vegetation, fire and human activities is derived from a relatively sparse collection of sediment cores, retrieved mostly from sites in the Greater Antilles and Mesoamerica (Figure 1.2).

Kennedy et al. (2006) collected a sediment core from a high-elevation site in the Dominican Republic and generated a 4,000 year-long multi-proxy record characterized by a persistent relationship between monotypic pine (*Pinus occidentalis*) forests and fire occurrence. *Pinus occidentalis* is endemic to Hispaniola and exhibits numerous adaptations to fire, including the development of a thick bark and high post-fire seedling recruitment (Darrow and Zanoni, 1990). Kennedy et al. (2006) noted that a regional shift toward more mesic conditions around 4,000 cal yr BP was associated with bog formation in their environmental record, and that periods of elevated aridity were marked by bog desiccation around 3,700 and 1,200 cal yr BP. A $\delta^{18}O$ and pollen record from Lake Miragoane, Haiti documented climate and environmental changes extending to >10,000 14C yr BP (Higuera-Gundy et al., 1999). The Haitian paleoenvironmental record suggested that climate was cool and dry as environments transitioned from the last glacial cycle and into the Holocene (Higuera-Gundy et al., 1999). Similar to

Kennedy et al. (2006), the authors found that wetter climates were present during the mid-Holocene, as recorded by forest expansion, and that there was a general trend of increasing aridity from Late Holocene to modern times (Higuera-Gundy et al., 1999).

Lane et al. (2009) presented multi-proxy sediment records retrieved from the Las Lagunas area of the Dominican Republic, documenting climate and environmental trends over the past ~3,000 years. The Las Lagunas records provided support for the notion that shifts in the mean position of the ITCZ had a strong influence on past Holocene precipitation variability in the Caribbean Basin (Hodell et al., 1991), in addition to improving understanding about the timing and magnitude of key climate events in the circum-Caribbean region. For example, the authors highlighted that decreased lake levels and increased ostracod $\delta^{18}O$ enrichment at ~1,200 cal yr BP in the Las Lagunas records could have been related to previously documented regionwide droughts, which researchers have postulated to have contributed to the Terminal Collapse of the Mayan civilization (Lane et al., 2009; Gill et al., 2007; Brenner et al., 2001). Despite the large body of evidence pointing to an environmentally deterministic model for rationalization of the Mayan collapse (i.e. an emphasis on climate and environmental changes leading to resource scarcity), other schools of thought advocate for alternative and/or more nuanced explanations, such as: political and economic restructuring and shifting trade patterns (Turner and Sabloff, 2012); human and agricultural diseases (Wilkinson, 1994; Brewbaker, 1979); and movement from generalizations about civilizational collapse to acknowledgement of societal resilience and sustainability (Graham, 2000; Aimers, 2007). Lane et al. (2009) also provided paleoecological evidence of a wet Medieval Warm Period (~950-650 cal yr BP) and dry Little Ice Age (~450-150 cal yr BP) in the Greater Antillean region.

Burney et al. (1994) analyzed a 7,000 year-long charcoal record from Laguna Tortuguero, Puerto Rico, and found that charcoal concentrations increased abruptly after ~5,300 cal yr BP, marking the start of a period of high fire activity, before declining at ~3,200 cal yr BP. The period of increased fire events was interpreted as a signal of early human arrival on the island and subsequent landscape burning, as the timing of the interval did not align with any known climate or environmental changes that offered a probable explanation for the increase in fire regimes (Burney et al., 1994). Similarly, Kjellmark (1996) identified an abrupt rise in charcoal levels and concomitant increase in pyrophitic pine (*Pinus caribaea*) woodlands at ~740 radiocarbon yr BP in a sediment core collected from Andros Island, Bahamas. However, it was inconclusive as to whether the observed charcoal and vegetation changes resulted from climate variability or prehistoric human activities due to dating uncertainties associated with the sediment core (Kjellmark, 1996).

Pollen and $\delta^{18}O$ isotopic values in a sediment core from Quintana Roo, Mexico suggested that climate became increasingly arid between 6,500 and 4,700 cal yr BP, with intensification of this drying trend at ~3,500 cal yr BP (Carrillo-Bastos et al., 2010). Similar to Lane et al. (2009), severe drought identified at ~1,200 cal yr BP was linked to regional aridity that was coeval with the Terminal Collapse of the Mayan empire, and $\delta^{18}O$ values indicated that the Medieval Warm Period was wet (Carrillo-Bastos et al., 2010). High ostracod $\delta^{18}O$ values indicated that lake levels declined in Petén, Guatemala, a major prehistoric Maya population center, at about AD 150, AD 550, and AD 850, coeval with various societal and population shifts throughout ancient Maya civilization history (Rosenmeier et al., 2002). Rosenmeier et al. (2002) noted that the observed $\delta^{18}O$ increases could be due to either enhanced evaporation or decreased freshwater

inflow as a result of vegetation regrowth, however their proxy data helps establish a pattern of repeated past connections between climate changes and the fate of Mayan civilization.

Correa-Metrio et al. (2012) examined the impacts of abrupt climate changes on the vegetation of the Yucatan Peninsula over much longer timescales than previously highlighted in the current review. Their sedimentary pollen record collected from Lake Petén-Itza, Guatemala extended back to 65,000 years ago, thus capturing the climate shifts associated with the Last Glacial Maximum (LGM) and several Heinrich events (Correa-Metrio et al., 2012). Heinrich events were associated with the proliferation of dry-adapted plant species, indicating arid climatic conditions, while the LGM was associated with a more muted vegetation response, thus demonstrating that very cold LGM climates in this region were relatively mesic compared to those of Heinrich events (Correa-Metrio et al., 2012). A shorter sedimentary record spanning the last ~3,800 years from the Yucatan Peninsula suggested that there was a shift from wet to arid climate conditions at ~3,500 cal yr BP as indicated by a decline in the pollen of mesic forest taxa (Aragón-Moreno et al., 2012). Furthermore, Aragón-Moreno et al. (2012) highlighted that the driest interval in their record at ~950 cal yr BP coincided temporally with the decline of the Classic Maya civilization, and that later increases in the pollen of tropical forest species at ~770 cal yr BP indicated a return to moist climate conditions during the Medieval Warm Period.

Schüpbach et al. (2015) assessed a suite of fire proxies—that is, both charcoal particles and the molecular biomarkers, levoglucosan, mannosan and galactosan—in a sediment core collected from Lake Petén-Itza to investigate linkages between fire, vegetation and anthropogenic activities over the course of the Holocene. The authors identified three peaks in fire activity: 1) 9,500-6,000 cal yr BP, 2) 3,700 cal yr BP, and 3) 2,700 cal yr BP (Schüpbach et al., 2015). The first period of increased fire activity (9,500-6,000 cal yr BP) was attributed to

enhanced fuel availability due to warmer and wetter climatic conditions, while the most recent peak in fire activity (2,700 cal yr BP) was attributed to Mayan use of fire for land clearance and farming (Schüpbach et al., 2015). The relative roles of Mayan agriculture and regional climate drying could not be determined with regards to the cause of the increase in fire activity at 3,700 cal yr BP (Schüpbach et al., 2015). Since the study by Schüpbach et al. (2015), the fire biomarker, levoglucosan, has been shown to accumulate on surficial seafloor sediments in the tropical Atlantic, therefore making marine sediment core investigations of linkages between biomass burning and climate and human activity viable; in conjunction with broadening the toolkit for analyzing fire histories (Schreuder et al., 2018).

The Little Ice Age was a period of abrupt climate cooling between ~ AD 1400 and ~ AD 1800, following the comparatively hotter Medieval Warm Period, which occurred between ~AD 800 and ~ AD 1300 (Mann *et al*., 2009; Grove, 2001; Hughes and Diaz, 1994). This review of paleoenvironmental records suggests that the Little Ice Age was marked by arid conditions, decreased lake levels, and declining tropical forest vegetation in the circum-Caribbean region. Contrastingly, the Medieval Warm Period was characterized by wet and humid conditions, increased lake levels, and expansion of tropical forest vegetation in the Caribbean. Furthermore, the paleoecological evidence suggests that the Caribbean Basin experienced arid conditions at approximately 1,200 cal yr BP to 1,000 cal yr BP and 3,500 cal yr BP to 3,200 cal yr BP, the former of which manifested as severe droughts that impacted major ancient civilizations within the region. These paleoclimatic inferences are corroborated by marine sediment core records collected from offshore northern South America (Haug et al., 2001; Peterson and Haug, 2006; Haug et al 2003), and indicates that Caribbean climate and environments have a strong dependency on large-scale Northern Hemisphere climate forcings, and are sensitive to variability

in the mean position of the ITCZ over millennial timescales—thus resulting in the expression of coherent, regional climate signals.

References

Aimers, J.J. 2007. What Maya collapse? Terminal classic variation in the Maya lowlands. *Journal of Archaeological Research* 15(4): 329-377.

Ali, A.A., Higuera, P.E., Bergeron, Y. and Carcaillet, C. 2009. Comparing fire-history interpretations based on area, number and estimated volume of macroscopic charcoal in lake sediments. *Quaternary Research* 72(3): 462-468.

Ammann, B., Birks, H.J.B., Brooks, S.J., Eicher, U., von Grafenstein, U., Hofmann, W., Lemdahl, G., Schwander, J., Tobolski, K. and Wick, L. 2000. Quantification of biotic responses to rapid climatic changes around the Younger Dryas—a synthesis. *Palaeogeography, Palaeoclimatology, Palaeoecology* 159(3): 313-347.

Aragón-Moreno, A.A., Islebe, G.A. and Torrescano-Valle, N. 2012. A~3800-yr, high-resolution record of vegetation and climate change on the north coast of the Yucatan Peninsula. *Review of Palaeobotany and Palynology* 178: 35-42.

Barker, D. 2012. Caribbean agriculture in a period of global change: vulnerabilities and opportunities. *Caribbean Studies* 40(2): 41-61.

Bellard, C., Leclerc, C. and Courchamp, F. 2014. Impact of sea level rise on the 10 insular biodiversity hotspots. *Global Ecology and Biogeography* 23(2): 203-212.

Bennett, K.D. and Willis, K.J. 2002. Pollen. In Tracking environmental change using lake sediments (pp. 5-32). Springer Netherlands.

Berchin, I.I., Valduga, I.B., Garcia, J. and de Andrade, J.B.S.O. 2017. Climate change and forced migrations: An effort towards recognizing climate refugees. *Geoforum* 84: 147-150.

Bigler, C. and Hall, R.I. 2002. Diatoms as indicators of climatic and limnological change in Swedish Lapland: a 100-lake calibration set and its validation for paleoecological reconstructions. *Journal of Paleolimnology* 27(1): 97-115.

Birks, H.H. and Birks, H.J.B. 2006. Multi-proxy studies in palaeolimnology. *Vegetation History and Archaeobotany* 15(4): 235-251.

Birks, H.J.B. and Birks, H.H. 2008. Biological responses to rapid climate change at the Younger Dryas—Holocene transition at Kråkenes, western Norway. *The Holocene* 18(1): 19-30.

Brenner, M., Hodell, D.A., Rosenmeier, M.F., Curtis, J.H., Binford, M.W. and Abbott, M.B. 2001. Abrupt climate change and pre-Columbian cultural collapse. In Interhemispheric climate linkages (pp. 87-103). Academic Press.

Brewbaker, J.L. 1979. Diseases of maize in the wet lowland tropics and the collapse of the Classic Maya civilization. *Economic Botany* 33(2): 101-118.

Brooks, S.J. 2006. Fossil midges (Diptera: Chironomidae) as palaeoclimatic indicators for the Eurasian region. *Quaternary Science Reviews* 25(15): 1894-1910.

Brooks, T.M., Mittermeier, R.A., Mittermeier, C.G., Da Fonseca, G.A., Rylands, A.B., Konstant, W.R., Flick, P., Pilgrim, J., Oldfield, S., Magin, G. and Hilton-Taylor, C. 2002. Habitat loss and extinction in the hotspots of biodiversity. *Conservation Biology* 16(4): 909-923.

Buckley, B.M., Anchukaitis, K.J., Penny, D., Fletcher, R., Cook, E.R., Sano, M., Wichienkeeo, A., Minh, T.T. and Hong, T.M. 2010. Climate as a contributing factor in the demise of Angkor, Cambodia. *Proceedings of the National Academy of Sciences* 107(15): 6748-6752.

Burn, M.J. and Palmer, S.E. 2014. Solar forcing of Caribbean drought events during the last millennium. *Journal of Quaternary Science* 29(8): 827-836.

Burney, D.A. 1997. Tropical islands as paleoecological laboratories: gauging the consequences of human arrival. *Human Ecology* 25(3): 437-457.

Burney, D.A., Burney, L.P. and MacPhee, R.D. 1994. Holocene charcoal stratigraphy from Laguna Tortuguero, Puerto Rico, and the timing of human arrival on the island. *Journal of Archaeological Science* 21(2): 273-281.

Burney, D.A., Robinson, G.S. and Burney, L.P. 2003. Sporormiella and the late Holocene extinctions in Madagascar. *Proceedings of the National Academy of Sciences* 100(19): 10800-10805.

Burney, L.P. and Burney, D.A. 2003. Charcoal stratigraphies for Kaua'i and the timing of human arrival. *Pacific Science* 57(2): 211-226.

Campbell, J.D., Taylor, M.A., Stephenson, T.S., Watson, R.A. and Whyte, F.S. 2011. Future climate of the Caribbean from a regional climate model. *International Journal of Climatology* 31(12): 1866-1878.

Carrillo-Bastos, A., Islebe, G.A., Torrescano-Valle, N. and González, N.E. 2010. Holocene vegetation and climate history of central Quintana Roo, Yucatán Península, Mexico. *Review of Palaeobotany and Palynology* 160(3): 189-196.

Castañeda, I.S. and Schouten, S. 2011. A review of molecular organic proxies for examining modern and ancient lacustrine environments. *Quaternary Science Reviews* 30(21): 2851-2891.

Chambers, F.M., Crowle, A., Daniell, J.R., Mauquoy, D., McCarroll, J., Sanderson, N., Thom, T., Toms, P. and Webb, J.C. 2017. Ascertaining the nature and timing of mire degradation: using palaeoecology to assist future conservation management in Northern England. *AIMS Environmental Science* 4(1): 54-82.

Chen, A.A. and Taylor, M.A. 2002. Investigating the link between early season Caribbean rainfall and the El Niño+ 1 year. *International Journal of Climatology* 22(1): 87-106.

Chiang, J.C. and Bitz, C.M. 2005. Influence of high latitude ice cover on the marine Intertropical Convergence Zone. *Climate Dynamics* 25(5): 477-496.

Chiang, J.C., Biasutti, M. and Battisti, D.S. 2003. Sensitivity of the Atlantic intertropical convergence zone to last glacial maximum boundary conditions. *Paleoceanography* 18(4).

Cincotta, R.P., Wisnewski, J. and Engelman, R. 2000. Human population in the biodiversity hotspots. *Nature* 404(6781): 990-992.

Clark, J.S., 1988. Particle motion and the theory of charcoal analysis: source area, transport, deposition, and sampling. *Quaternary Research* 30(1): 67-80.

Cohen, A.S. 2017. The past is a key to the future: Lessons paleoecological data can provide for management of the African Great Lakes. *Journal of Great Lakes Research*. doi: https://doi.org/10.1016/j.jglr.2017.10.001

Constable, A.L. 2017. Climate change and migration in the Pacific: options for Tuvalu and the Marshall Islands. *Regional Environmental Change* 17(4): 1029-1038.

Cook, K.H. and Vizy, E.K. 2010. Hydrodynamics of the Caribbean low-level jet and its relationship to precipitation. *Journal of Climate* 23(6): 1477-1494.

Corlett, R.T. 2012. Climate change in the tropics: the end of the world as we know it?. *Biological Conservation* 151(1): 22-25.

Correa-Metrio, A., Bush, M.B., Hodell, D.A., Brenner, M., Escobar, J. and Guilderson, T. 2012. The influence of abrupt climate change on the ice-age vegetation of the Central American lowlands. *Journal of Biogeography* 39(3): 497-509.

Daniau, A.L., Goñi, M.F.S., Martinez, P., Urrego, D.H., Bout-Roumazeilles, V., Desprat, S. and Marlon, J.R. 2013. Orbital-scale climate forcing of grassland burning in southern Africa. *Proceedings of the National Academy of Sciences* 110(13): 5069-5073.

Darrow, W.K. and Zanoni, T. 1990. Hispaniolan pine (*Pinus occidentalis* Swartz) a little known sub-tropical pine of economic potential. *The Commonwealth Forestry Review*: 133-146.

Dávalos, L.M. and Russell, A.L. 2012. Deglaciation explains bat extinction in the Caribbean. *Ecology and Evolution* 2(12): 3045-3051.

Dávalos, L.M. and Turvey, S.T. 2012. West Indian mammals: the old, the new, and the recently extinct. Bones, clones and biomes: the history and geography of recent neotropical mammals: 157-202.

Davis, M.B. 2000. Palynology after Y2K—understanding the source area of pollen in sediments. *Annual Review of Earth and Planetary Sciences* 28(1): 1-18.

Davis, M.B. and Shaw, R.G. 2001. Range shifts and adaptive responses to Quaternary climate change. *Science* 292(5517): 673-679.

Davis, O.K. 1987. Spores of the dung fungus *Sporormiella*: increased abundance in historic sediments and before Pleistocene megafaunal extinction. *Quaternary Research* 28(2): 290-294.

Denis, E.H., Toney, J.L., Tarozo, R., Anderson, R.S., Roach, L.D. and Huang, Y. 2012. Polycyclic aromatic hydrocarbons (PAHs) in lake sediments record historic fire events: validation using HPLC-fluorescence detection. *Organic Geochemistry* 45: 7-17.

Deutsch, C.A., Tewksbury, J.J., Huey, R.B., Sheldon, K.S., Ghalambor, C.K., Haak, D.C. and Martin, P.R. 2008. Impacts of climate warming on terrestrial ectotherms across latitude. *Proceedings of the National Academy of Sciences* 105(18): 6668-6672.

Diamond, J. 2009. Archaeology: Maya, Khmer and Inca. *Nature* 461(7263): 479-480.

Donohoe, A., Marshall, J., Ferreira, D. and Mcgee, D. 2013. The relationship between ITCZ location and cross-equatorial atmospheric heat transport: From the seasonal cycle to the Last Glacial Maximum. *Journal of Climate* 26(11): 3597-3618.

Dubois, N., Saulnier-Talbot, É., Mills, K., Gell, P., Battarbee, R., Bennion, H., Chawchai, S., Dong, X., Francus, P., Flower, R. and Gomes, D.F. 2018. First human impacts and responses of aquatic systems: A review of palaeolimnological records from around the world. *The Anthropocene Review* 5(1): 28-68.

Dunning, N.P. and Beach, T. 2010. Farms and forests: Spatial and temporal perspectives on ancient Maya landscapes. In Landscapes and societies (pp. 369-389). Springer Netherlands.

Dunning, N.P., Beach, T.P. and Luzzadder-Beach, S. 2012. Kax and kol: Collapse and resilience in lowland Maya civilization. *Proceedings of the National Academy of Sciences* 109(10): 3652-3657.

Elias, V.O., Simoneit, B.R., Cordeiro, R.C. and Turcq, B. 2001. Evaluating levoglucosan as an indicator of biomass burning in Carajas, Amazonia: A comparison to the charcoal record. *Geochimica et Cosmochimica Acta* 65(2): 267-272.

Elsner, J.B. 2006. Evidence in support of the climate change–Atlantic hurricane hypothesis. *Geophysical Research Letters* 33(16), L16705, doi: 10.1029/2006GL026869.

Etienne, D. and Jouffroy-Bapicot, I. 2014. Optimal counting limit for fungal spore abundance estimation using Sporormiella as a case study. *Vegetation history and Archaeobotany* 23(6): 743-749.

Evans, D., Pottier, C., Fletcher, R., Hensley, S., Tapley, I., Milne, A. and Barbetti, M. 2007. A comprehensive archaeological map of the world's largest preindustrial settlement complex at Angkor, Cambodia. *Proceedings of the National Academy of Sciences* 104(36): 14277-14282.

Evans, D.H., Fletcher, R.J., Pottier, C., Chevance, J.B., Soutif, D., Tan, B.S., Im, S., Ea, D., Tin, T., Kim, S. and Cromarty, C., 2013. Uncovering archaeological landscapes at Angkor using LIDAR. *Proceedings of the National Academy of Sciences* 110(31): 12595-12600.

Faegri, K., Kaland, P.E. and Krzywinski, K. 1989. Textbook of pollen analysis (No. Ed. 4). John Wiley & Sons Ltd.

Gagan, M.K., Ayliffe, L.K., Beck, J.W., Cole, J.E., Druffel, E.R.M., Dunbar, R.B. and Schrag, D.P. 2000. New views of tropical paleoclimates from corals. *Quaternary Science Reviews* 19(1): 45-64.

Gamble, D.W., Parnell, D.B. and Curtis, S. 2008. Spatial variability of the Caribbean mid-summer drought and relation to north Atlantic high circulation. *International Journal of Climatology* 28(3): 343-350.

Giannini, A., Kushnir, Y. and Cane, M.A. 2000. Interannual variability of Caribbean rainfall, ENSO, and the Atlantic Ocean. *Journal of Climate* 13(2): 297-311.

Gill, J.L., McLauchlan, K.K., Skibbe, A.M., Goring, S., Zirbel, C.R. and Williams, J.W. 2013. Linking abundances of the dung fungus *Sporormiella* to the density of bison: implications for assessing grazing by megaherbivores in palaeorecords. *Journal of Ecology* 101(5): 1125-1136.

Gill, R.B., Mayewski, P.A., Nyberg, J., Haug, G.H. and Peterson, L.C. 2007. Drought and the Maya collapse. *Ancient Mesoamerica* 18(2): 283-302.

Graham, E. 2000. Collapse, conquest and Maya survival at Lamanai, Belize. *Archaeology International* 4: 52-56.

Grinsted, A., Moore, J.C. and Jevrejeva, S. 2013. Projected Atlantic hurricane surge threat from rising temperatures. *Proceedings of the National Academy of Sciences* 110(14): 5369-5373.

Grove, J.M. 2001. The initiation of the" Little Ice Age" in regions round the North Atlantic. *Climatic Change* 48(1): 53-82.

Hall, T.C., Sealy, A.M., Stephenson, T.S., Kusunoki, S., Taylor, M.A., Chen, A.A. and Kitoh, A. 2013. Future climate of the Caribbean from a super-high-resolution atmospheric general circulation model. *Theoretical and Applied Climatology* 113(1-2): 271-287.

Harrison, R.D., Sreekar, R., Brodie, J.F., Brook, S., Luskin, M., O'Kelly, H., Rao, M., Scheffers, B. and Velho, N. 2016. Impacts of hunting on tropical forests in Southeast Asia. *Conservation Biology* 30(5): 972-981.

Hastenrath, S. and Polzin, D. 2013. Climatic variations in Central America and the Caribbean. *International Journal of Climatology* 33(6): 1348-1356.

Haug, G.H., Günther, D., Peterson, L.C., Sigman, D.M., Hughen, K.A. and Aeschlimann, B. 2003. Climate and the collapse of Maya civilization. *Science* 299(5613): 1731-1735.

Haug, G.H., Hughen, K.A., Sigman, D.M., Peterson, L.C. and Röhl, U. 2001. Southward migration of the intertropical convergence zone through the Holocene. *Science* 293(5533): 1304-1308.

Hedges, S.B. 1996. Historical biogeography of West Indian vertebrates. *Annual Review of Ecology and Systematics* 27(1): 163-196.

Heiri, O., Lotter, A.F. and Lemcke, G. 2001. Loss on ignition as a method for estimating organic and carbonate content in sediments: reproducibility and comparability of results. *Journal of Paleolimnology* 25(1): 101-110.

Hendrickson, M. 2010. Historic routes to Angkor: development of the Khmer road system (ninth to thirteenth centuries AD) in mainland Southeast Asia. *Antiquity* 84(324): 480-496.

Higuera-Gundy, A., Brenner, M., Hodell, D.A., Curtis, J.H., Leyden, B.W. and Binford, M.W. 1999. A 10,300 14 C yr record of climate and vegetation change from Haiti. *Quaternary Research* 52(2): 159-170.

Hodell, D.A., Curtis, J.H., Brenner, M. 1995. Possible role of climate in the collapse of Classic Maya civilization. *Nature* 375 (6530): 391–394.

Hodell, D.A., Curtis, J.H., Jones, G.A., Higuera-Gundy, A., Brenner, M., Binford, M.W. and Dorsey, K.T. 1991. Reconstruction of Caribbean climate change over the past 10,500 years. *Nature* 352(6338): 790-793.

Hughes, M.K. and Diaz, H.F. 1994. Was there a 'Medieval Warm Period', and if so, where and when?. *Climatic Change* 26(2-3): 109-142.

Iglesias, V., Yospin, G.I. and Whitlock, C. 2015. Reconstruction of fire regimes through integrated paleoecological proxy data and ecological modeling. *Frontiers in Plant Science* 5: 785.

Isaac, B.L. 1983. The Aztec" Flowery War": A Geopolitical Explanation. *Journal of Anthropological Research* 39(4): 415-432.

Johnsen, S.J., Dahl-Jensen, D., Gundestrup, N., Steffensen, J.P., Clausen, H.B., Miller, H., Masson-Delmotte, V., Sveinbjörnsdottir, A.E. and White, J. 2001. Oxygen isotope and palaeotemperature records from six Greenland ice-core stations: Camp Century, Dye-3, GRIP, GISP2, Renland and NorthGRIP. *Journal of Quaternary Science* 16(4): 299-307.

Jones, P.D. and Mann, M.E. 2004. Climate over past millennia. *Reviews of Geophysics* 42(2).

Jury, M., Malmgren, B.A. and Winter, A. 2007. Subregional precipitation climate of the Caribbean and relationships with ENSO and NAO. *Journal of Geophysical Research: Atmospheres* 112(D16).

Keatings, K.W., Heaton, T.H.E. and Holmes, J.A. 2002. Carbon and oxygen isotope fractionation in non-marine ostracods: results from a 'natural culture' environment. *Geochimica et Cosmochimica acta* 66(10): 1701-1711.

Kennedy, L.M., Horn, S.P. and Orvis, K.H. 2006. A 4000-year record of fire and forest history from Valle de Bao, Cordillera Central, Dominican Republic. *Palaeogeography, Palaeoclimatology, Palaeoecology* 231(3): 279-290.

Kennett, D.J., Breitenbach, S.F., Aquino, V.V., Asmerom, Y., Awe, J., Baldini, J.U., Bartlein, P., Culleton, B.J., Ebert, C., Jazwa, C. and Macri, M.J. 2012. Development and disintegration of Maya political systems in response to climate change. *Science* 338(6108): 788-791.

Knutson, T.R., McBride, J.L., Chan, J., Emanuel, K., Holland, G., Landsea, C., Held, I., Kossin, J.P., Srivastava, A.K. and Sugi, M. 2010. Tropical cyclones and climate change. *Nature Geoscience* 3(3): 157-163.

Lachniet, M.S., Asmerom, Y., Burns, S.J., Patterson, W.P., Polyak, V.J. and Seltzer, G.O. 2004. Tropical response to the 8200 yr BP cold event? Speleothem isotopes indicate a weakened early Holocene monsoon in Costa Rica. *Geology* 32(11): 957-960.

Lambert, W.J., Aharon, P. and Rodriguez, A.B. 2008. Catastrophic hurricane history revealed by organic geochemical proxies in coastal lake sediments: a case study of Lake Shelby, Alabama (USA). *Journal of Paleolimnology* 39(1): 117-131.

Lane, C.S., Horn, S.P., Mora, C.I. and Orvis, K.H. 2009. Late-Holocene paleoenvironmental change at mid-elevation on the Caribbean slope of the Cordillera Central, Dominican Republic: a multi-site, multi-proxy analysis. *Quaternary Science Reviews* 28(23): 2239-2260.

Laurance, W.F., Goosem, M. and Laurance, S.G. 2009. Impacts of roads and linear clearings on tropical forests. *Trends in Ecology & Evolution* 24(12): 659-669.

Laurance, W.F., Sayer, J. and Cassman, K.G. 2014. Agricultural expansion and its impacts on tropical nature. *Trends in Ecology & Evolution* 29(2): 107-116.

Leng, M.J. and Marshall, J.D. 2004. Palaeoclimate interpretation of stable isotope data from lake sediment archives. *Quaternary Science Reviews* 23(7): 811-831.

Lewsey, C., Cid, G. and Kruse, E. 2004. Assessing climate change impacts on coastal infrastructure in the Eastern Caribbean. *Marine Policy* 28(5): 393-409.

Lister, G.S., Kelts, K., Zao, C.K., Yu, J.Q. and Niessen, F. 1991. Lake Qinghai, China: closed-basin like levels and the oxygen isotope record for ostracoda since the latest Pleistocene. *Palaeogeography, Palaeoclimatology, Palaeoecology* 84(1-4): 141-162.

Liu, K.B. and Fearn, M.L. 2000. Reconstruction of prehistoric landfall frequencies of catastrophic hurricanes in northwestern Florida from lake sediment records. *Quaternary Research* 54(2): 238-245.

Longrich, N.R. and Olson, S.L. 2011. The bizarre wing of the Jamaican flightless ibis *Xenicibis xympithecus*: a unique vertebrate adaptation. *Proceedings of the Royal Society of London B: Biological Sciences*: p.rspb20102117.

Lotter, A.F. 2003. Multi-proxy climatic reconstructions. *Global Change in the Holocene*: 373-383.

M. C. Peel, B. L. Finlayson, T. A. Mcmahon. 2007. Updated world map of the Köppen-Geiger climate classification. Hydrology and Earth System Sciences Discussions, European Geosciences Union 4 (2): 439-473. <hal-00298818>

Mann, M.E., Zhang, Z., Rutherford, S., Bradley, R.S., Hughes, M.K., Shindell, D., Ammann, C., Faluvegi, G. and Ni, F. 2009. Global signatures and dynamical origins of the Little Ice Age and Medieval Climate Anomaly. *Science* 326(5957): 1256-1260.

Mantsis, D.F. and Clement, A.C. 2009. Simulated variability in the mean atmospheric meridional circulation over the 20th century. *Geophysical Research Letters* 36(6).

Martin, E.R. and Schumacher, C. 2011. Modulation of Caribbean precipitation by the Madden–Julian oscillation. *Journal of Climate* 24(3): 813-824.

Maslin, M.A. and Burns, S.J. 2000. Reconstruction of the Amazon Basin effective moisture availability over the past 14,000 years. *Science* 290(5500): 2285-2287.

Masson, V., Vimeux, F., Jouzel, J., Morgan, V., Delmotte, M., Ciais, P., Hammer, C., Johnsen, S., Lipenkov, V.Y., Mosley-Thompson, E. and Petit, J.R. 2000. Holocene climate variability in Antarctica based on 11 ice-core isotopic records. *Quaternary Research* 54(3): 348-358.

Maxwell, A.L. 2004. Fire regimes in north-eastern Cambodian monsoonal forests, with a 9300-year sediment charcoal record. *Journal of Biogeography* 31(2): 225-239.

Mcandrews, J.H. 1988. Human disturbance of North American forests and grasslands: the fossil pollen record. In Vegetation history (pp. 673-697). Springer, Dordrecht.

McClenachan, L. and Cooper, A.B. 2008. Extinction rate, historical population structure and ecological role of the Caribbean monk seal. *Proceedings of the Royal Society of London B: Biological Sciences* 275(1641): 1351-1358.

McNeil, C.L. 2012. Deforestation, agroforestry, and sustainable land management practices among the Classic period Maya. *Quaternary International* 249: 19-30.

Medina-Elizalde, M. and Rohling, E.J. 2012. Collapse of Classic Maya civilization related to modest reduction in precipitation. *Science* 335(6071): 956-959.

Menon, S., Soberón, J., Li, X. and Peterson, A.T. 2010. Preliminary global assessment of terrestrial biodiversity consequences of sea-level rise mediated by climate change. *Biodiversity and Conservation* 19(6): 1599-1609.

Milner-Gulland, E.J. and Bennett, E.L. 2003. Wild meat: the bigger picture. *Trends in Ecology & Evolution* 18(7): 351-357.

Mittermeier, R.A., Myers, N., Thomsen, J.B., da Fonseca, G.A. and Olivieri, S. 1998. Biodiversity hotspots and major tropical wilderness areas: approaches to setting conservation priorities. *Conservation Biology* 12(3): 516-520.

Mittermeier, R.A., Robles Gil, P., Hoffmann, M., Pilgrim, J., Brooks, T., Mittermeier, C.G., Lamoreux, J., da Fonseca, G.A.B. 2004. Hotspots revisited: Earth's biologically richest and most endangered ecoregions. CEMEX, Mexico City, Mexico.

Moore, W., Elliott, W. and Lorde, T. 2017. Climate change, Atlantic storm activity and the regional socio-economic impacts on the Caribbean. *Environment, Development and Sustainability* 19(2): 707-726.

Morgan, G.S. and Woods, C.A. 1986. Extinction and the zoogeography of West Indian land mammals. *Biological Journal of the Linnean Society* 28(1-2): 167-203.

Myers, N. 1988. Threatened biotas:" hot spots" in tropical forests. *Environmentalist* 8(3): 187-208.

Myers, N., Mittermeier, R.A., Mittermeier, C. G., da Fonseca, G.A. and Kent, J. 2000. Biodiversity hotspots for conservation priorities. *Nature* 403: 853-858.

Nogué, S., de Nascimento, L., Froyd, C.A., Wilmshurst, J.M., de Boer, E.J., Coffey, E.E., Whittaker, R.J., Fernández-Palacios, J.M. and Willis, K.J. 2017. Island biodiversity conservation needs palaeoecology. *Nature Ecology & Evolution* 1(7): s41559-017.

O'Brien, D. 2011. CARICOM: Regional Integration in a Post-Colonial World. *European Law Journal* 17(5): 630-648.

Osborne, P.L. 2000. Tropical ecosystems and ecological concepts. Cambridge University Press, pp. 1-6.

Parducci, L., Bennett, K.D., Ficetola, G.F., Alsos, I.G., Suyama, Y., Wood, J.R. and Pedersen, M.W. 2017. Ancient plant DNA in lake sediments. *New Phytologist* 214(3): 924-942.

Parducci, L., Matetovici, I., Fontana, S.L., Bennett, K.D., Suyama, Y., Haile, J., Kjær, K.H., Larsen, N.K., Drouzas, A.D. and Willerslev, E. 2013. Molecular-and pollen-based vegetation analysis in lake sediments from central Scandinavia. *Molecular Ecology* 22(13): 3511-3524.

Peters, M.E. and Higuera, P.E. 2007. Quantifying the source area of macroscopic charcoal with a particle dispersal model. *Quaternary Research* 67(2): 304-310.

Peterson, L.C. and Haug, G.H. 2006. Variability in the mean latitude of the Atlantic Intertropical Convergence Zone as recorded by riverine input of sediments to the Cariaco Basin (Venezuela). *Palaeogeography, Palaeoclimatology, Palaeoecology* 234(1): 97-113.

Pregill, G.K. and Olson, S.L. 1981. Zoogeography of West Indian vertebrates in relation to Pleistocene climatic cycles. *Annual Review of Ecology and Systematics* 12(1): 75-98.

Pulwarty, R.S., Nurse, L.A. and Trotz, U.O. 2010. Caribbean islands in a changing climate. *Environment* 52(6): 16-27.

Raczka, M.F., Bush, M.B., Folcik, A.M. and McMichael, C.H. 2016. Sporormiella as a tool for detecting the presence of large herbivores in the Neotropics. *Biota Neotropica* 16(1).

Raper, D. and Bush, M. 2009. A test of Sporormiella representation as a predictor of megaherbivore presence and abundance. *Quaternary Research* 71(3): 490-496.

Rosenmeier, M.F., Hodell, D.A., Brenner, M., Curtis, J.H. and Guilderson, T.P. 2002. A 4000-year lacustrine record of environmental change in the southern Maya lowlands, Peten, Guatemala. *Quaternary Research* 57(2): 183-190.

Russell, J.M. and Johnson, T.C. 2005. Late Holocene climate change in the North Atlantic and equatorial Africa: Millennial-scale ITCZ migration. *Geophysical Research Letters* 32(17).

Sanford Jr, R.L. and Horn, S.P. 2000. Holocene rain-forest wilderness: a neotropical perspective on humans as an exotic, invasive species. *USDA Forest Service Proceedings RMRS* 3: 1-15.

Santiago-Valentin, E. and Olmstead, R.G. 2004. Historical biogeography of Caribbean plants: introduction to current knowledge and possibilities from a phylogenetic perspective. *Taxon* 53(2): 299-319.

Santley, R. 1985. The Political Economy of the Aztec Empire. *Journal of Anthropological Research* 41(3): 327-337.

Schoonmaker, P.K. and Foster, D.R. 1991. Some implications of paleoecology for contemporary ecology. *The Botanical Review* 57(3): 204-245.

Schreuder, L.T., Hopmans, E.C., Stuut, J.B.W., Damsté, J.S.S. and Schouten, S. 2018. Transport and deposition of the fire biomarker levoglucosan across the tropical North Atlantic Ocean. *Geochimica et Cosmochimica Acta* 227: 171-185.

Schüpbach, S., Kirchgeorg, T., Colombaroli, D., Beffa, G., Radaelli, M., Kehrwald, N.M. and Barbante, C. 2015. Combining charcoal sediment and molecular markers to infer a Holocene fire history in the Maya Lowlands of Petén, Guatemala. *Quaternary Science Reviews* 115: 123-131.

Schwalb, A., Burns, S.J. and Kelts, K. 1999. Holocene environments from stable isotope stratigraphy of ostracods and authigenic carbonate in Chilean Altiplano Lakes. *Palaeogeography, Palaeoclimatology, Palaeoecology* 148(1): 153-168.

Scott, D., Simpson, M.C. and Sim, R. 2012. The vulnerability of Caribbean coastal tourism to scenarios of climate change related sea level rise. *Journal of Sustainable Tourism* 20(6): 883-898.

Seppä, H. and Bennett, K.D. 2003. Quaternary pollen analysis: recent progress in palaeoecology and palaeoclimatology. *Progress in Physical Geography* 27(4): 548-579.

Seto, K.C., Güneralp, B. and Hutyra, L.R. 2012. Global forecasts of urban expansion to 2030 and direct impacts on biodiversity and carbon pools. *Proceedings of the National Academy of Sciences* 109(40): 16083-16088.

Smith, M.E. and Berdan, F.F. 1992. Archaeology and the Aztec empire. *World Archaeology* 23(3): 353-367.

Smol, J.P. and Douglas, M.S. 2007. From controversy to consensus: making the case for recent climate change in the Arctic using lake sediments. *Frontiers in Ecology and the Environment* 5(9): 466-474.

Smol, J.P., Wolfe, A.P., Birks, H.J.B., Douglas, M.S., Jones, V.J., Korhola, A., Pienitz, R., Rühland, K., Sorvari, S., Antoniades, D. and Brooks, S.J. 2005. Climate-driven regime shifts in the biological communities of arctic lakes. *Proceedings of the National Academy of Sciences of the United States of America* 102(12): 4397-4402.

Sobel, A.H., Camargo, S.J., Hall, T.M., Lee, C.Y., Tippett, M.K. and Wing, A.A. 2016. Human influence on tropical cyclone intensity. *Science* 353(6296): 242-246.

Soto-Centeno, J.A. and Steadman, D.W. 2015. Fossils reject climate change as the cause of extinction of Caribbean bats. *Scientific Reports* 5: 7971.

Spencer, J.D., Brunelle, A. and Hepola, T. 2017. Using Paleoecology to Inform Land Management as Climates Change: An Example from an Oak Savanna Ecosystem. *Environmental Management* 60(6): 1090-1100.

Steadman, D.W., Martin, P.S., MacPhee, R.D., Jull, A.T., McDonald, H.G., Woods, C.A., Iturralde-Vinent, M. and Hodgins, G.W. 2005. Asynchronous extinction of late Quaternary sloths on continents and islands. *Proceedings of the National Academy of Sciences of the United States of America* 102(33): 11763-11768.

Steadman, D.W., Pregill, G.K. and Olson, S.L. 1984. Fossil vertebrates from Antigua, Lesser Antilles: evidence for late Holocene human-caused extinctions in the West Indies. *Proceedings of the National Academy of Sciences* 81(14): 4448-4451.

Stivrins, N., Soininen, J., Amon, L., Fontana, S.L., Gryguc, G., Heikkilä, M., Heiri, O., Kisielienė, D., Reitalu, T., Stančikaitė, M. and Veski, S. 2016. Biotic turnover rates during the Pleistocene-Holocene transition. *Quaternary Science Reviews* 151: 100-110.

Stouffer, R.J., Yin, J., Gregory, J.M., Dixon, K.W., Spelman, M.J., Hurlin, W., Weaver, A.J., Eby, M., Flato, G.M., Hasumi, H. and Hu, A. 2006. Investigating the causes of the response of the thermohaline circulation to past and future climate changes. *Journal of Climate* 19(8): 1365-1387.

Sugita, S. 1994. Pollen representation of vegetation in Quaternary sediments: theory and method in patchy vegetation. *Journal of Ecology*: 881-897.

Taylor, M.A., Enfield, D.B. and Chen, A.A. 2002. Influence of the tropical Atlantic versus the tropical Pacific on Caribbean rainfall. *Journal of Geophysical Research: Oceans* 107(C9).

Taylor, M.A., Stephenson, T.S., Chen, A.A. and Stephenson, K.A. 2012. Climate change and the Caribbean: Review and response. *Caribbean Studies* 40(2): 169-200.

Tewksbury, J.J., Huey, R.B. and Deutsch, C.A. 2003. Putting the Heat on Tropical Animals. *Science* 301: 100.

Thompson, J.E.S. 1974. Maya astronomy. *Philosophical Transactions of the Royal Society of London A: Mathematical, Physical and Engineering Sciences* 276(1257): 83-98

Thompson, L.G., Mosley-Thompson, E. and Henderson, K.A. 2000. Ice-core palaeoclimate records in tropical South America since the Last Glacial Maximum. *Journal of Quaternary Science* 15(4): 377-394.

Thompson, R., Battarbee, R.W., O'sullivan, P.E. and Oldfield, F. 1975. Magnetic susceptibility of lake sediments. *Limnology and Oceanography* 20(5): 687-698.

Turner, B.L. and Sabloff, J.A. 2012. Classic Period collapse of the Central Maya Lowlands: Insights about human–environment relationships for sustainability. *Proceedings of the National Academy of Sciences* 109(35): 13908-13914.

Uyarra, M.C., Cote, I.M., Gill, J.A., Tinch, R.R., Viner, D. and Watkinson, A.R. 2005. Island-specific preferences of tourists for environmental features: implications of climate change for tourism-dependent states. *Environmental Conservation* 32(1): 11-19.

von Grafenstein, U., Erlernkeuser, H. and Trimborn, P. 1999. Oxygen and carbon isotopes in modern fresh-water ostracod valves: assessing vital offsets and autecological effects of interest for palaeoclimate studies. *Palaeogeography, Palaeoclimatology, Palaeoecology* 148(1): 133-152.

Walsh, K.J., McBride, J.L., Klotzbach, P.J., Balachandran, S., Camargo, S.J., Holland, G., Knutson, T.R., Kossin, J.P., Lee, T.C., Sobel, A. and Sugi, M. 2016. Tropical cyclones and climate change. *Wiley Interdisciplinary Reviews: Climate Change* 7(1): 65-89.

Webster, D. 2000. The not so peaceful civilization: A review of Maya war. *Journal of World Prehistory* 14(1): 65-119.

Werner, L. 1992. Cultivating the secrets of Aztec gardens. *Americas* 44: 6–16.

Wetzel, F.T., Kissling, W.D., Beissmann, H. and Penn, D.J. 2012. Future climate change driven sea-level rise: secondary consequences from human displacement for island biodiversity. *Global Change Biology* 18(9): 2707-2719.

Whitlock, C., Colombaroli, D., Conedera, M. and Tinner, W. 2017. Land-use history as a guide for forest conservation and management. *Conservation Biology*. doi: 10.1111/cobi.12960.

Wilkinson, R.L. 1994. Yellow fever: Ecology, epidemiology, and role in the collapse of the Classic lowland Maya civilization. *Medical Anthropology* 16(1-4): 269-294.

Williams, J.W. and Jackson, S.T. 2007. Novel climates, no-analog communities, and ecological surprises. *Frontiers in Ecology and the Environment* 5(9): 475-482.

Williams, J.W., Jackson, S.T. and Kutzbach, J.E. 2007. Projected distributions of novel and disappearing climates by 2100 AD. *Proceedings of the National Academy of Sciences* 104(14): 5738-5742.

Wingard, G.L., Bernhardt, C.E. and Wachnicka, A. 2017. The role of paleoecology in restoration and resource management—The past as a guide to future decision-making: Review and example from the Greater Everglades Ecosystem, USA. *Frontiers in Ecology and Evolution* 5: 11. doi: 10.3389/fevo.

Wood, J.R., Wilmshurst, J.M., Turney, C.S. and Fogwill, C.J. 2016. Palaeoecological signatures of vegetation change induced by herbivory regime shifts on subantarctic Enderby Island. *Quaternary Science Reviews* 134: 51-58.

Wu, L., Li, C., Yang, C. and Xie, S.P. 2008. Global teleconnections in response to a shutdown of the Atlantic meridional overturning circulation. *Journal of Climate* 21(12): 3002-3019.

Wu, X., Liang, X.Z. and Zhang, G.J. 2003. Seasonal migration of ITCZ precipitation across the equator: Why can't GCMs simulate it?. *Geophysical Research Letters* 30(15).

Yadava, M.G. and Ramesh, R. 2005. Monsoon reconstruction from radiocarbon dated tropical Indian speleothems. *The Holocene* 15(1): 48-59.

Yamamoto, L. and Esteban, M. 2017. Migration as an Adaptation Strategy for Atoll Island States. *International Migration* 55(2): 144-158.

Zolitschka, B., Francus, P., Ojala, A.E. and Schimmelmann, A. 2015. Varves in lake sediments–a review. *Quaternary Science Reviews* 117: 1-41.

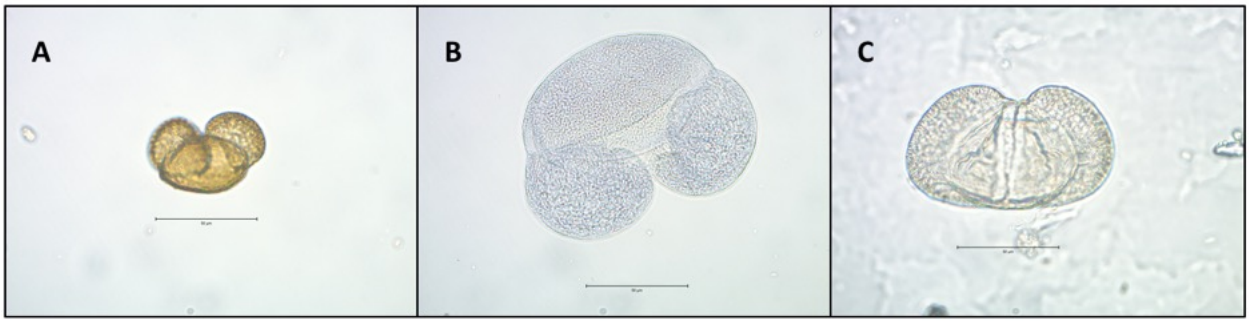

Figure 1. 1 Representative pollen grains extracted from prehistoric lake sediments.
The pollen grains displayed are from species in the family *Pinaceae*, including A) Eastern white pine (*Pinus strobus*), B) Balsam fir (*Abies balsamea*), and C) White spruce (*Picea glauca*) (scale bars=50 μm). Images taken by Mario Williams using a Nikon Eclipse Ci series light microscope at 40 × magnification fitted with a SPOT digital imaging camera.

Figure 1. 2 The Caribbean region highlighting paleoecological study sites from text.

1) Kennedy et al. (2006), Valle de Bao, Dominican Republic (19° N, 71° W); 2) Higuera-Gundy et al. (1999), Lake Miragoane, Haiti (18° N, 73° W); 3) Lane et al. (2009), Las Lagunas, Dominican Republic (18° N, 70° W); 4) Burney et al. (1994), Laguna Tortuguero, Puerto Rico (18° N, 66° W); 5) Kjellmark (1996), Church's Blue Hole, Bahamas (25° N, 78° W); 6) Carrillo-Bastos et al. (2010), Lake Tzib, Mexico (19° N, 88° W); 7) Rosenmeier et al. (2002), Lake Salpetén, Guatemala (16° N, 89° W); 8) Correa-Metrio et al. (2012), Lake Petén-Itza, Guatemala (16° N, 89° W); 9) Aragón-Moreno et al. (2012), Ría Lagartos Biosphere Reserve, Mexico (21° N, 88° W); 10) Schüpbach et al. (2015), Lake Petén-Itza, Guatemala (16° N, 89° W).

CHAPTER 2

A MULTI-PROXY RECONSTRUCTION OF HOLOCENE CLIMATE AND ENVIRONMENTAL CHANGES IN JAMAICA, WEST INDIES

Introduction

Climate variability and extreme climate events, such as droughts and hurricanes, pose major challenges to the economic security and welfare of Jamaican peoples, with the potential for particularly significant impacts in key commercial sectors, such as agriculture and tourism (Selvaraju et al., 2013; Gamble et al., 2010; Hyman, 2014). While the emergence of climate adaptation strategies among local groups that will be significantly affected by future climate shifts is promising (Beckford et al., 2007; Campbell et al., 2011; Dhar and Khirfan, 2016), the uncertainty and potential severity associated with the global climate problem enjoins us to leverage science-based knowledge to help improve possible climate mitigation outcomes. For example, the frequency of high-magnitude North Atlantic hurricanes (category four and five) is projected to increase with future climate changes (Knutson et al., 2010; Bender et al., 2010), and Jamaica's agricultural sector experienced economic losses totaling ~14.4 billion JMD due to extreme climate events (e.g. hurricanes, heavy winds, landslides etc.) between 1994 and 2010 (Selvaraju et al., 2013)—thus highlighting the potential socioeconomic costs associated with mismanagement of future climate risks. Average temperature over Jamaica has increased by ~0.6 °C since the mid-20th century, and increases of 0.47 °C to 1.17 °C and 0.6 °C to 2.3 °C are expected by the years 2030 and 2060, respectively (McSweeney et al., 2008). General circulation model projections also point to decreasing precipitation for Jamaica by the year 2100

(McSweeney et al., 2008), while sea level within the Caribbean is expected to rise by 0.5-0.6 m over a similar timeframe (Nurse et al., 2014).

The native flora of Jamaica consists of ~3,003 species, of which ~26% are endemic to the island (Colon, 1996). Furthermore, Jamaica's vegetation has the fifth highest percentage of endemic species among islands globally (Davis et al., 1997). The island also has biodiverse wildlife communities, which include 505 endemic terrestrial snails, 22 endemic amphibians, 33 endemic reptiles, 31 endemic birds and 4 endemic mammals (NEPA, 2010). Jamaican Quaternary deposits have produced fossils of 49 vertebrate species, including 3 amphibians, 18 reptiles, 9 birds, and 19 mammals (Morgan, 1993). Of the 49 species represented in this fossil vertebrate fauna, 15 are either globally extinct or locally extirpated, including the burrowing owl (*Speotyto cunicularia*), Jamaican flightless ibis (*Xenicibis xympithecus*), the Jamaican rice rat (*Oryzomys antillarum*), and the Jamaican monkey (*Xenothrix mcgregori*) (Morgan, 1993). A reanalysis of last appearance dates in the fossil record of West Indian mammals indicated that the abrupt climate changes of the Last Glacial Maximum and last glacial-interglacial transition were not associated with major extinctions (MacPhee, 2009). Instead, the observed pattern of extinctions suggested that most West Indian mammalian losses occurred between prehistoric settlement of the Caribbean (~6,000 years ago) and the European colonial period (~AD 1500 to AD 1850) and was a consequence of a plethora of long-term human impacts, such as habitat modification and the introduction of exotic competitors (e.g. Old World rats) and predators (e.g. the Indian mongoose, *Herpestes auropunctatus*) (MacPhee, 2009).

Few paleoenvironmental studies have been conducted in Jamaica, indicating that there is a particularly urgent need for research that investigates the climatic and ecological history of the island, and can be utilized to guide and enhance future management of the country's natural

resources. McFarlane et al. (2002) analyzed a suite of bioarcheological materials and calcite deposits from the Jackson Bay cave system in central-southern Jamaica, and found that climates were dry during the last glacial-interglacial transition (~16,500-10,000 14C YBP), cycled between dry and wet conditions from ~10,000-2,000 14C YBP, wet from 2,000-700 14C YBP, and dry from 700 14C YBP to modern times. Similar to McFarlane et al. (2002), a sediment core collected from Wallywash Pond, located close to the southwestern coast of Jamaica, suggested that the island was dry and cool during the late Pleistocene-Holocene transition up to 9,500 yr BP, after which climates cycled through alternating phases of mesic and arid conditions throughout the Holocene (Street-Perrott et al., 1993). The specific timing of these Holocene climatic fluctuations was not determined in their study due to core dating issues associated with ancient carbon contamination (Street-Perrott et al., 1993). Nonetheless, Street-Perrott et al.'s (1993) paleoclimatic inferences were later corroborated by geochemical and ostracod faunal analyses (Holmes, 1998; Holmes et al. 1995) conducted using the same Wallywash Pond sediment core from the 1993 study. Geochemical analysis of coastal lake sediments collected from southeastern Jamaica indicated that the Little Ice Age was associated with drought conditions and coincided with reduced solar forcing and a southern shift of the Intertropical Convergence Zone (ITCZ) (Burn and Palmer, 2014).

Archaeological records suggest that Jamaica was first colonized after AD 600 by the Ostionoid peoples (Rouse, 1992). The coastal disposition of most Ostionoid archaeological sites as well as the discovery of associated deposits that contain marine faunal remains (e.g. large fishes, sea turtles and shellfish, such as queen conch, *Strombus gigas*) indicates a diet that was heavily reliant on marine resources (Atkinson, 2006). The Meillacan peoples colonized the island approximately 300 years later (~AD 900) and established both coastal and interior settlements,

therefore exhibiting a weaker dependence on the marine environment than their Ostionoid counterparts (Atkinson, 2006). The Taino culture developed on the island around AD 1200 (Atkinson, 2006), and persisted until European arrival in 1494. The Tainos practiced a broad diversity of subsistence strategies, including fishing, hunting and foraging for wild plants (Parry, 1955); however, their dietary needs were primarily met through small-scale agriculture. The Tainos cultivated cassava (*Manihot utilissima*), sweet potato (*Ipomoea batatas*) (Parry, 1955), maize (*Zea mays*), marunguey (*Zamia* sp.), cocoyam (*Xanthosoma* sp.), common bean (*Phaseolus vulgaris*), yampi (*Dioscorea trifida*), squashes (*Cucurbita* sp.), and pineapple (*Ananas comosus*), among other crops (Mickleburgh and Pagán-Jiménez, 2012; Rashford, 1993). The prehistoric peoples that occupied Jamaica were known to use slash-and-burn methods for agricultural land clearance (Waters et al., 1993). Caribbean prehistoric peoples used the Jamaican hutia (*Geocapromys brownii*) and rice rat (*Oryzomys* sp.) as terrestrial dietary protein sources (Henry, 2018). The percentage of Jamaican hutia (*Geocapromys brownii*) and rice rat (*Oryzomys* sp.) faunal remains exhibited an increase at inland sites relative to coastal sites for Jamaica, and St. Martin and St. Kitts, respectively (Wing, 2008). Consequently, small land mammals may have been an important dietary component for Caribbean prehistoric peoples, particularly if access to coastal food resources was limited or if securing those resources was otherwise time- or energy-intensive (Wing, 2008).

The established date of first human arrival for Jamaica (~1300 cal yr BP) greatly diverges from dates for the nearby Greater Antillean islands of Cuba, Hispaniola and Puerto Rico. The available evidence offers several candidate regions for the potential geographic origin of the earliest settlers of the Greater Antilles, including the Yucatan Peninsula, northeastern South America, the Panamanian Isthmus and its surrounding lands, and the southeastern United States

(Keegan et al., 2013). The earliest archeological date for human settlement of Cuba has a radiocarbon age of ~5,140 14C yr BP (Kozlowski, 1974). The earliest date of first human settlement for Hispaniola, ~5,580 14C yr BP (Moore, 1991), was obtained from radiocarbon dating of marine shells, and application of a correction factor to account for marine reservoir effects yields the age, 5,780 cal yr BP (MacPhee, 2009). Based on a series of eight radiocarbon dates, Puerto Rico's earliest accepted archaeological site, Maruca, was estimated to have been occupied between 4,840 cal yr BP and 3,895 cal yr BP (Rodríguez, 1999). Burney et al. (1994) proposed that an abrupt increase in charcoal fragments recorded in a sediment core from Laguna Tortuguero, Puerto Rico at ~5,300 cal yr BP was indicative of first human impacts associated with colonization of the island. However, a coeval charcoal spike recorded in a sediment core collected from the neighboring island of Hispaniola was speculated to have been caused by regional climate changes—that is, wetter conditions leading to increased fuel loads coupled with enhanced seasonality—rather than human burning of the landscape (Higuera-Gundy et al., 1999). Given the closeness and large sizes of these islands, and the maritime capabilities of prehistoric Caribbean explorers (i.e. "very capable seafarers") (Fitzpatrick, 2013), the relatively late date of first human arrival in Jamaica appears anomalous in the broader context of Greater Antillean settlement. This discrepancy may reflect the need for increased allocation of resources towards archaeological sampling effort in Jamaica, the loss of archaeological sites due to Holocene sea level rise (Digerfeldt and Hendry, 1987) or destructive human activities, or a relative difficulty in locating Jamaican archaeological sites as a result of the occurrence of small prehistoric populations organized in highly dispersed habitation patterns.

Jamaica is estimated to have been inhabited by ~600,000 Tainos when Christopher Columbus landed on the island in 1494 (Duerden, 1895). By the time of English conquest of the

island in 1655, it is thought that the Taino were extirpated due to forced labor by the Spanish, and the introduction of infectious Old World diseases such as smallpox, measles, typhus, and yellow fever (Duerden, 1895; Renny, 1807; Montenegro and Stephens, 2006). Sugar cane (*Saccharum officinarum*) agriculture was introduced to the Caribbean in 1494, however the sugar industry did not become firmly established in Jamaica until the early 1500s (Woodward, 2006). By 1805, Jamaica was the world's foremost sugar exporter, with more than 800 sugar estates operating on the island (Higman, 2001). Livestock agriculture—primarily cattle, but also pigs and sheep—also thrived during the late 18th to mid-19th century, such that by 1881 there were over 600 livestock pens on the island (Higman, 2001). In contrast to the period between the 16th and 18th centuries, which was marked by widespread forest clearance for the establishment of sugar plantations (Eyre, 1996, 1986, 1987), the mid to late 19th century was a period of forest expansion in Jamaica, as slaves were granted full emancipation in 1838 and the sugar economy deteriorated shortly thereafter (Eyre, 1987; Higman, 2001; Satchell, 1990). The number of sugar plantations peaked at 859 in 1804, and then declined to 646 in 1834, 266 in 1869, and by 1910 only 74 sugar plantations were active on the island (Sheridan, 1989). More recent drivers of land cover change in Jamaica include bauxite mining and urban expansion (Álvarez-Berríos, 2013). Estimates of annual deforestation rates range from 0.1% from 1989-1998 (Evelyn and Camirand, 2003) and 3.9% from 1987-1992 (Tole, 2002) to 5.3% from 1980-1990 (Ehrhardt-Martinez, 1998). The degree to which prehistoric to modern land use and land cover modifications are reflected in the sedimentary record of Jamaica is unknown.

The following study is the first multi-proxy analysis of its kind done in Jamaica as a result of the novel range of environmental proxies used. I examine the sedimentary record of pollen, charcoal, ostracod $\delta^{18}O$ and $\delta^{13}C$, and dung fungal spores in a lake sediment core, to

develop an integrated paleoecological framework for understanding Holocene climate and environmental changes on the island. Assessment of the timing of appearance and abundances of the proxies in lake sediments provides critical insights into past environmental responses to climate fluctuations and a variety of anthropogenic events—including prehistoric human settlement by early Amerindians and the implementation of colonial plantation agriculture. This study contributes to a growing body of literature that provides the spatial and temporal context necessary for developing a framework for understanding the evolution of human-environment dynamics in the Caribbean (Mueller et al., 2018; Hooghiemstra et al., 2018; Castilla-Beltrán et al., 2018; Bain et al., 2018; Royer et al., 2017; LeBlanc et al., 2017); and provides baselines of past climate and ecological states (e.g. variability, responses, rates, and amplitudes etc.) to aid targeted, data-driven biodiversity conservation in tropical island environments (Nogué et al., 2017).

Materials and Methods

Site Description

Jamaica (18° N, 77° W) is located in the northwestern Caribbean Sea and is the third largest island (10,900 km^2) in the Greater Antilles, behind Cuba (110,860 km^2) and Hispaniola (76,192 km^2). The island is situated south of Cuba, west-southwest of Haiti, north of Panama, and east of the Yucatán Peninsula. Jamaica has a population of ~2.9 million people and a GDP of ~14.03 billion USD (World Bank, 2017). Jamaica has a subtropical climate with a summer wet season and winter dry season, which aligns with general patterns of Caribbean precipitation—however, rainfall is significantly modified on local scales by orography and elevation (Chen and Taylor, 2008). The moisture-laden north-east trade winds rise as they encounter the island's

central range of mountains and high plateaus. As they ascend, the air masses cool and heavy precipitation occurs over the windward slopes of the high-elevation areas. The consequent effects of this orographic rainfall pattern are an up to fourfold difference in average annual rainfall between the wet mountainous interior portions of the island (e.g. northeastern Blue Mountains region, > 5000 feet) and the arid northern and southern coastal strips, and a particularly pronounced rain shadow effect on the southern and southwestern plains of the island (Nkemdirim, 1979; Guernsey, 1941) (Figure 2.1). Jamaica experiences tropical cyclones that are associated with the annual North Atlantic hurricane season, which reaches peak intensity from August to October (Landsea, 1993). Consequently, precipitation maxima on the island coincide with peak rainfall accumulation during the hurricane season (Figure 2.1).

Wallywash Pond (Figure 2.2) (Saint Elizabeth, Jamaica, 17° N, 77° W, area=0.76 km^2, 7 m ASL) is a shallow freshwater lake (max. depth, 5 m; avg. depth, 2.8 m) that is situated in a low-elevation depression constrained by the bifurcated upward and downward thrust zones of the Pondside fault (Benford et al., 2015). The lake is surrounded by alluvium and is underlain and bordered to the east by the limestones of the Miocene age Newport Formation of the White Limestone Group—Jamaica's most extensive lithological unit (Benford et al., 2015). The lake basin is bordered by the town of Black River to the north-west, the Black River Lower Morass Ramsar-protected wetland to the west and north, and the Pedro Plains to the east and south-east, which extend coastward from the foot of the Santa Cruz Mountains.

Precipitation across the parish of Saint Elizabeth varies greatly with northern areas close to the west-central interior uplands (e.g. Cockpit Country region) receiving more rainfall annually (~80-100 inches) than southern coastal areas (~40-60 inches)—and in particular, coastal regions that lie in the rain shadow of the Santa Cruz Mountains (Nkemdirim, 1979; Campbell et

al., 2011). The average annual rainfall for the town of Black River, Saint Elizabeth is ~50 inches (1263 mm) (Jamaica Meteorological Service, 2019b), while the average annual temperature for the Sangster International Airport, Saint James is ~82 °F (27.6 °C) (Jamaica Meteorological Service, 2019a). Meteorological information is presented for Black River and Sangster International Airport due to a paucity of more geographically specific climate data for the Wallywash Pond area. Nonetheless, the close proximity of those sites to Wallywash Pond relative to the expected variability of the climate data over the given spatial area provides confidence in the representativity of the presented information. A small man-made outlet channel flows from Wallywash Pond's larger northern basin to Parottee Pond, a saline waterbody that abuts the coast to the north-west of Wallywash Pond. Wallywash Pond is spring-fed at a rate of ~0.04 m^3 s^{-1} (US Army Corps of Engineers, 2001).

Vegetation

We conducted a vegetation survey on February 6, 2018 to document the plant community composition and structure of the Wallywash Pond basin. Initial plant observations were made along a low sloping ridge overlooking the western shoreline of the lake, before traversing a section of the lake perimeter to characterize the littoral and aquatic plant communities. Plant identification was conducted to the species level, or to the lowest taxonomic level possible, for all cases. In total, 111 individual plant taxa were recorded from the upland, lowland, littoral and aquatic environments of the Wallywash Pond basin (Table 2.1). Relative abundances of the identified plants were qualitatively determined based on the estimated number of individuals encountered on the day of the vegetation survey. Plants characteristic of dry limestone forests in Jamaica were specially identified to support scientific investigation of this globally threatened forest ecosystem, and in recognition of its high conservation value (Janzen, 1988; Miles et al.,

2006; Portillo-Quintero and Sánchez-Azofeifa, 2010; Dirzo et al., 2011). The cultivation and endemic status of each plant taxa was also recorded.

The upland slope adjacent to the lake was dominated by dense thickets of *Croton humilis* (Pepper Rod), and the tree species, *Haematoxylum campechianum* (Logwood), *Bursera simaruba* (Red Birch), and *Samanea saman* (Guango). The lowlands were dominated by *Sida acuta* (Broom Weed), *Vernonia cinerea*, *Malvastrum americanum*, *Malvastrum coromandelianum*, *Prosopis juliflora* (Mesquite), and grasses, including *Andropogon pertusus* (Seymour Grass) and *Andropogon bicornis* (Foxtail Grass). Dense stands of *Typha domingensis* (Reedmace) dominated the littoral zone, along with *Eleocharis elegans* and *Centella asiatica*. *Potamogeton nodosus* was the dominant aquatic vegetation.

The flora of the Black River Lower Morass wetland area, which borders Wallywash Pond, includes the emergents, *Cladium jamaicense* (Sawgrass), *Schoenoplectus americanus*, and *Sagittaria lancifolia* (Arrowhead). The mangrove species, *Conocarpus erectus* (Buttonwood) and *Rhizophora mangle* (Red Mangrove) are also well-represented. Common tree species include the palms, *Sabal jamaicensis* (Bull Thatch), *Roystonea princeps*, and *Calyptronoma occidentalis*, in addition to *Grias cauliflora* (Anchovy Pear), *Symphonia globulifera* (Boar Gum), and *Ficus*. Other commonly encountered taxa include, the herbs, *Dieffenbachia* and *Ludwigia*, and human cultivars such as the fruit tree, *Mangifera indica* (Mango), and *Cannabis sativa* (Ganja) (Garrick, 1986).

Core collection, initial description and sampling

We collected a sediment core (WALL18) on February 5, 2018 from close to the middle-western shore of Wallywash Pond (17°58.057’ N, 077°48.379 W; 3.1 m depth) (Figure 2.2), using a 5.08 cm modified Livingstone piston corer deployed from an anchored coring platform.

The coring platform consisted of two inflatable kayaks secured with ratchet straps to an overlaid sheet of plywood. The sediment-water interface was obtained using a Bolivia adapter fitted with ~7 cm-diameter polycarbonate tubing (0-52 cm; Drive #1). Subsequent drives (52-392 cm) using only the 5.08 cm modified Livingstone piston corer included: Drive #2 (52-142 cm), Drive #3 (142-242 cm), Drive #4 (242-322 cm), and Drive #5 (322-392 cm). The total length of WALL18 was 3.92 m. Average sediment recovery for each 1 m drive was 88%. Sediment losses of 10% and 20% were recorded for the bases of Drive #2 and Drive #4 respectively, as a result of piston slippage during core extrusion. The lower 30% of basal Drive #5 was not retrieved as it terminated in a previously documented thin stratigraphic layer of coarse marl (Street-Perrott et al., 1993) that was difficult to penetrate. Core material from each drive was measured in the field, and then wrapped in plastic cling wrap, encased in halved polyvinyl chloride tubes, and secured with vinyl adhesive tape.

Each core segment was split lengthwise into two halves at the National Lacustrine Core Facility (University of Minnesota, Minneapolis, MN). Halved core segments were then imaged using a Geotek Geoscan high-resolution digital photography system, and initial core description—including documentation of sediment color and composition, and the presence/absence of plant macrofossils and shells—was facilitated by using PSICAT 0.9.8 and CoreWall/Corelyzer 2.0.4. Half of each core segment was stored at the National Lacustrine Core Facility in the Lacustrine Core Repository and each corresponding half was shipped to the University of Maine (Orono, Maine) for further study ('working half'). All collected sediment was stored at ~4 °C to inhibit sediment microbial activity and suppress bacterial and fungal growth. The working half of each core segment was sliced transversely into 0.5 cm thick discs, which were stored individually in sealed, plastic Whirl-Pak bags for subsequent subsampling.

Chronology

We submitted three samples containing concentrated macrocharcoal fragments to the University of Georgia-Center for Applied Isotope Studies facility for AMS ^{14}C radiocarbon dating (Table 2.2). The three radiocarbon dates were calibrated using the IntCal09 radiocarbon calibration curve (Reimer et al. 2009) to account for atmospheric variations in ^{14}C production over time due to changes in solar activity (Stuiver and Quay, 1980). The Bacon software, which uses Bayesian statistics to calculate age-depth relationships for sediment cores (Blaauw and Christen, 2011), was used to generate an age-depth model in R (R Development Core Team, 2013) (Figure 2.3). One of the dates (198.25 cm, Lab # 39644; Table 2.2) was not included in the age-depth model because the Bacon program rejects age reversals based on the assumption that dates should appear in stratigraphic order. The age reversal may have been caused by reworking of younger materials to depth due to post-depositional disruption as a result of bioturbation in the lake sediments or high-intensity fluvial processes, such as flooding. An additional date (8,250 yr BP±100, 392 cm, Lab # Ors-2789; Table 2.2) based on previous radiometric dating of the white marl layer (Street-Perrott et al., 1993) at the base of WALL18 was included in our age-depth model, thus facilitating establishment of a basal age constraint for the sediment core. Ages are reported in calendar years before present (cal yr BP)—unless specified otherwise—with 'present' defined as AD 1950 to account for the spike in atmospheric radiocarbon levels due to the use of atomic weapons in the mid-20th century (De Vries, 1958; Rafter and Fergusson, 1957).

Pollen and charcoal analyses

1 cm^3 subsamples were used for pollen analysis at 8 cm intervals for WALL18. Subsamples were obtained using a calibrated 1 cm^3 brass volumetric sampler. Samples were processed at the University of Maine using a modified version of the protocol for fossil pollen

concentration developed by Faegri and Iverson (1989). A 1 cm^3 solution containing a known quantity of plastic microspheres (5×10^4 microspheres/ml) developed by the National Lacustrine Core Facility was added to each sample to enable calculation of pollen concentrations (number of pollen grains/cm^3). Humic acids and carbonates were removed from each sample using 10% potassium hydroxide and 10% hydrochloric acid respectively. Samples were then screened through 160 μm mesh to remove large organic particles and sand grains. The 10% hydrochloric acid treatment was repeated for samples with excess carbonates. Glacial acetic acid was used to remove water from each sample before treatment with acetic anhydride and concentrated sulfuric acid to remove organic materials. Samples were then rinsed with 95% ethanol, dehydrated with tert-butyl alcohol, and then suspended in silicone oil for storage and mounting on glass slides for microscopy. Pollen grains and fern and fungal spores were identified using a Nikon Labophot-2 microscope. A minimum of 300 terrestrial pollen grains were counted for each sample. Pollen and spore identification were facilitated by the use of published keys (e.g. Roubik and Moreno, 1991; Willard et al., 2004; Sivaram, 2013; Gelorini et al., 2011; Cugny et al., 2010), online databases and reference materials. PolyCounter software (Nakagawa, 2007) version 3.1.4 was used to record pollen and spore counts, and to generate rarefaction curves to determine the degree to which pollen counts estimated the palynological richness of each sample—that is, rarefaction curves level off when additional counting effort fails to identify new taxa. Pollen abundances are represented as a percentage of the terrestrial and aquatic pollen sum. Fungal spores were not included in the pollen sums for percentage calculations and are represented as abundance counts. A stratigraphically constrained incremental sum-of-squares analysis (CONISS) was performed using Tilia (Grimm, 1987) version 2.1.1 to delineate major ecological zones based on compositional changes in the plant and fungal communities.

1 cm^3 subsamples were used for charcoal analysis at continuous 0.5 cm intervals for WALL18. Subsamples were obtained using a calibrated 1 cm^3 brass volumetric sampler. Charcoal samples were processed using a modified version of the methodology outlined by Whitlock and Larson (2001). ~25 ml of 15% hydrogen peroxide and ~5 ml of 70% ethanol were added to each sample. Ethanol prevented charcoal pieces from moving up the sides of the flasks and clinging during heating. Samples were placed in the drying oven at 50 °C for 24 hours to disaggregate and bleach the sediment. Samples were wet sieved through a 250 µm mesh and then transferred into a plastic petri dish for counting. All charcoal pieces in each sample were counted using a stereoscope to determine charcoal concentrations (number of charcoal pieces/cm^3). CharAnalysis (Higuera et al., 2009 and 2010) version 1.1 for Matlab software was used to convert charcoal concentrations into charcoal accumulation rates (CHAR, number of charcoal pieces/cm^2/year). Low frequency background CHAR was estimated using a Lowess smoother with a 500-year smoothing window. CHAR values that exceed background CHAR levels are interpreted as representing periods of increased fire activity.

Ostracods and stable isotope analyses

1 cm^3 subsamples were obtained at ~4 cm intervals in WALL18 from layers that had sufficient ostracod concentrations to yield the required quantity (≥ 50 µg of carbonate) for analysis. Samples were treated with 7% hydrogen peroxide to disaggregate sediments and then wet sieved through a 125 µm mesh. Samples were transferred into a plastic petri dish and ostracods of the species *Cypretta brevisaepta* were identified, cleaned and picked under a stereoscope using a fine paintbrush. We used *Cypretta brevisaepta* only because of its high abundances throughout WALL18 and to avoid inconsistencies associated with interspecific differences in isotopic fractionation (von Grafenstein et al., 1999). A minimum of 10 ostracod

valves or 5 intact ostracods were picked for each sample. Ostracod identification was facilitated by the use of published keys (Pérez et al., 2010; Furtos, 1936). Picked ostracods were transferred with distilled water into microcentrifuge tubes and then dried at 25 °C. We submitted 47 samples to the University of Arizona Environmental Isotope Laboratory for stable oxygen and carbon isotope analysis. Stable oxygen and carbon isotope measurements are represented as the ratio of $^{18}O/^{16}O$ (± 0.10, 1σ SD) and $^{13}C/^{12}C$ (± 0.08, 1σ SD) respectively, relative to the VPDB standard.

Results

Lithology

WALL18 is characterized by a layer of white marl from 0-179 cm, dark brown carbonate mud from 179-242 cm, and black organic mud from 242-388 cm and 390-392 cm. A thin bed of white marl lies between the black organic mud layers from 388-390 cm (Figure 2.4). Both fragmented and intact gastropod and mollusk shells were abundant from 0-242 cm. There was a conspicuous absence of shelly material at core depths lower than 242 cm. The black organic mud layers were densely interspersed with plant material.

Pollen and spores

Zone WP-1 (1,594 cal yr BP-1,378 cal yr BP/ AD 356-AD 572): Vascular cryptogam spores were present in relatively high abundances (~30%) in this basal zone, with *Polypodiaceae* (common ferns) reaching abundances of ≥ 20% and *Achrostichum aureum* (mangrove fern) present at comparatively low abundances (< 5%). Mangrove values ranged from ~15-45% and were represented primarily by *Conocarpus erectus* (~10-45%) and *Rhizophora mangle* at lower abundances (< 5%). Trees and shrubs and upland herbs were represented equally with each having values that ranged between ~10-20%. *Myrtaceae* was present with abundances of ~10%, and this zone was the only one where *Hieronyma* was present in the vegetation record (< 5%).

Aquatic vascular plants had very low abundances (< 5%), while emergent taxa (primarily *Cyperaceae*) had high abundances (~35%) at the base of the zone but declined sharply to < 5% near the transition to the adjacent zone. *Poaceae* had low abundances (~5%), while *Amaranthaceae* was not initially represented but increased slightly towards the end of the zone to ~5%. Fungal spores were absent from this zone. Pollen and spore abundances indicate mangrove-fern swamp vegetation dominated by *Conocarpus erectus*, common ferns, and sedges (Figure 2.4). High abundances of swamp and emergent taxa indicate low lake levels (Figure 2.4).

Zone WP-2 (1,378 cal yr BP-982 cal yr BP/ AD 572-AD 968): *Amaranthaceae* dominated this zone with abundances ranging between 45-75%. Trees and shrubs were at their lowest abundances for the whole vegetation record (< 5%), while upland herbs were highly abundant and ranged from ~50-85%. *Asteraceae* abundances increased (≤ 10%) relative to those observed in basal zone WP-1 (< 1%). The abundance of aquatic vascular plants also increased sharply (~10-50%) and was driven by a large increase in *Potamogeton nodosus*, which ranged from ~10-50%. In contrast, emergents had low abundances (≤ 10%) and declined gradually throughout this zone. Low *Cyperaceae* abundances of ≤ 10% parallel this trend. *Conocarpus erectus* abundances declined sharply to ~5% and ferns were absent. Fungal spores were absent from this zone. The decline of *Conocarpus erectus*, ferns, and sedges and coeval spike in abundances of *Amaranthaceae* and *Asteraceae*, in conjunction with increased abundances of the aquatic species *Potamogeton nodosus*, indicate a rise in lake levels and shift from a mangrove-fern swamp community to a disturbed forbland ecosystem (Figure 2.4). The pioneering ruderal taxa *Amaranthaceae* and *Asteraceae* are considered strong indicators of disturbance, and ceteris paribus, their abundances respond positively to land clearance and denudation (Clement and Horn, 2001; Mcandrews, 1988; Dull, 2007; Wahl et al., 2007; Rosenmeier et al., 2002).

Zone WP-3 (982 cal yr BP-938 cal yr BP/ AD 968-AD 1012): Trees and shrubs increased in abundance to ~75%. *Trema* and *Cecropia* had abundances of ~55% and ~10% respectively. Upland herbs had relatively low abundances (~15%), and *Amaranthaceae* and *Poaceae* were represented equally with each having values of ~5%. Aquatic vascular plants were not detected in this zone and emergent taxa had low abundances (~5%). *Conocarpus erectus* was present in low abundances (~5%) while *Rhizophora mangle* and ferns were absent. *Bursera simaruba*, *Prosopis juliflora*, *Grias cauliflora*, *Urtica*, *Cassia*, *Crotalaria verrucosa*, *Solanum* and *Fabaceae* were all present in low abundances (≤ 5%). *Sporormiella* spores appeared in low abundances (~2 spores) in this ecological zone, while *Cercophora* spores were comparatively abundant (~13 spores). *Trema* and *Cecropia* are shade-intolerant, gap-colonizing pioneer species (Brokaw, 1987; Pearson et al., 2003; Fujisaka et al., 2000). The presence of *Trema* and *Cecropia* in high abundances coupled with the presence of dry limestone forest taxa, such as *Bursera simaruba* and *Cassia* (Table 2.1), in low abundances, indicates an open, early successional dry forest community and post-disturbance recovery (Figure 2.4). Low abundances or absences of emergent taxa, aquatic vascular plants, and mangroves suggest decreased lake levels (Figure 2.4).

Zone WP-4 (433 cal yr BP-114 cal yr BP/ AD 1517-AD 1836): Trees and shrubs gradually declined from ~30% at the base of this zone to ~10%. *Trema* declined from ~15% to < 2%, while *Prosopis juliflora* was present at low abundances (≤ 2%) throughout the zone. *Haematoxylum campechianum* (Logwood) first appeared in this zone at low abundances (< 2%) at ~276 cal yr BP (AD 1674). *Haematoxylum campechianum* was introduced to Jamaica in AD 1715 primarily for cultivation for the production of dyes and construction of fences (Allison, 1999; Kahr et al., 1998; Higman, 2001), consequently our age model (Figure 2.3) estimates the

date of introduction of the species to the island accurately to within ~40 years. Upland herbs were present at abundances of ~35% throughout the zone. *Mimosa*, *Amaranthaceae*, and *Desmodium incanum* were each present at low abundances (< 2%) throughout the zone, while *Asteraceae* had abundances of ~2-5%. The herbs *Mimosa* and *Desmodium* are indicative of disturbance (Lozano-García et al., 2007 and 2010). *Poaceae* gradually increased in abundance from ~10% at the base of the zone to ~25%. The cultivars *Saccharum officinarum* (Sugar cane) and *Cannabis sativa* (hemp) first appeared in this zone at low abundances (< 2%). Vascular cryptogams were present at low abundances < 2%. Aquatic vascular plants increased in abundance from ~20% at the base of the zone to ~50%. *Potamogeton nodosus* (Longleaf pondweed) increased sharply from < 2% at the base of the zone to ~50%, while *Nymphaea ampla* (Dotleaf waterlily) declined from ~15% to less than < 2%. *Potamogeton nodosus* is commonly found in nutrient-rich waters (Robach et al., 1996; Kuhar et al., 2011; Bakker et al., 2013), while *Nymphaea ampla* is intolerant of eutrophication (Lucero, 2018; Lucero et al., 2015; Pelaez et al., 2014); therefore the observed increase in *Potamogeton nodosus* abundances and concomitant decline of *Nymphaea ampla* may be reflective of changes in water quality, and is consistent with an increase in trophic status of Wallywash Pond during this interval. Emergents were present at abundances of ≤ 10% throughout the zone. *Sporormiella* and *Cercophora* fungal spores were present throughout this interval and peaked in their abundances in the middle of the zone with ~30 spores and ~25 spores respectively. *Sordaria* first appeared in the zone with low abundances (~2 spores) throughout the interval. The gradual decline of arboreal pollen, consistent presence of herbaceous disturbance taxa (e.g. *Asteraceae*, *Amaranthaceae*, *Desmodium* and *Mimosa*), increased abundances of *Poaceae*, appearance of cultivated species (i.e. *Haematoxylum campechianum, Saccharum officinarum* and *Cannabis sativa*), increased

abundances of *Potamogeton nodosus* and decline of *Nymphaea ampla*, and increased abundances of dung fungal spores indicate an open, pastoral landscape under the influence of anthropogenic pressures, such as land clearance, and livestock and crop agriculture (Figure 2.4).

Zone WP-5 (114 cal yr BP-Present/ AD 1836-Present): Upland herbs dominate with abundances of ~60% throughout the zone. *Poaceae* had high abundances of 30-50%, while *Urtica*, *Asteraceae*, *Amaranthaceae*, *Solanum* and *Croton humilis* were present in low abundances (~2%). Trees and shrubs were present in relatively low abundances (~15%) throughout the zone. *Haematoxylum campechianum*, *Prosopis juliflora* and *Pinus caribaea* had low abundances (~2%). *Pinus caribaea* first appeared in this zone at ~28 cal yr BP (AD 1922). *Pinus caribaea* is native to Central America, western Cuba and the Bahamas (Birks and Barnes, 1990), and was introduced to Jamaica in AD 1945 for the establishment of commercial plantations for timber and pulpwood (Liegel, 1991). Appearance of *Pinus caribaea* in our vegetation record approximates the timing of the mid-20th century introduction of the species to Jamaica and its subsequent proliferation as a commercial timber crop. Aquatic vascular plants declined from ~15% at the base of the zone to ~5%. *Potamogeton nodosus* declined from ~10% to < 2%, *Nymphaea ampla* was absent in this zone. Emergent taxa increased from ~10% to ~15% with *Cyperaceae* and *Typha* present at low abundances (~2%) throughout the zone. The mangrove species *Conocarpus erectus* and *Rhizophora mangle* were absent from this zone. Recent declines in mangrove abundances may be linked to the overharvesting of mangrove timber for charcoal production, construction of beach huts, and other artisanal uses (FAO, 2007). *Sporormiella* and *Cercophora* had high abundances with maximum counts of ~45 spores and ~30 spores respectively. *Sordaria* was also present at lower abundances (~2 spores). The dominance of upland herbs, increased abundances of *Poaceae*, relatively low abundances of

arboreal taxa, and high abundances of dung fungal spores indicate an open landscape under the influence of pastoral activities, such as land clearance and livestock grazing (Figure 2.4). High *Poaceae* abundances in conjunction with a decline in aquatic vascular plants (e.g. *Potamogeton nodosus*) and consistent representation of emergent taxa (e.g. *Cyperaceae* and *Typha*) point to an increase in aridity and declining lake levels (Figure 2.4).

Charcoal analysis

Fire activity was low with no charcoal accumulation rates (CHAR) above background CHAR between ~4,850 cal yr BP (~2,900 BC/~351 cm) and ~1,370 cal yr BP (~AD 580/~206 cm) (Figure 2.5). An increase in CHAR (~22 # pieces/cm^2/yr) above background CHAR at ~1,370 cal yr BP (~AD 580/~206 cm) indicated the earliest surge in fire activity (Figure 2.5). This rise in fire activity directly preceded the start of ecological zone WP-2 (Figure 2.4). The period between ~1290 cal yr BP (~AD 660/~201 cm) and ~1160 cal yr BP (~AD 790/~190 cm) marked an interval of sustained CHAR above background CHAR, and included the highest recorded CHAR levels (~96 # pieces/cm^2/yr) in our fire reconstruction at ~1,240 cal yr BP (~AD 710/~197 cm) (Figure 2.5). This period coincided with an abrupt vegetation shift at the base of ecological zone WP-2 (Figure 2.4). A sharp increase in CHAR (~78 # pieces/cm^2/yr) above background CHAR at ~1050 cal yr BP (~AD 900/~178 cm) indicated a surge in fire activity (Figure 2.5) and occurred at the end of ecological zone WP-2 (Figure 2.4). The period of intensified fire regimes (i.e. enhanced and persistent fire activity) between ~1290 cal yr BP (~AD 660/~201 cm) and ~1050 cal yr BP (~AD 900/~178 cm) (Figure 2.5) approximated the boundaries of ecological zone WP-2 (Figure 2.4). CHAR declined below background CHAR between ~1050 cal yr BP (~AD 900/~178 cm) and ~740 cal yr BP (~AD 1210/~129 cm), which indicated a period of decreased fire activity. A comparatively smaller increase in CHAR (~4 #

pieces/cm^2/yr) above background CHAR was recorded at ~740 cal yr BP (~AD 1210/~129 cm), which marked a rise in fire activity but at a magnitude below that of the period between ~1290 cal yr BP (~AD 660/~201 cm) and ~1050 cal yr BP (~AD 900/~178 cm) (Figure 2.5). CHAR declined below background CHAR between ~700 cal yr BP (~AD 1250/~123 cm) and ~460 cal yr BP (~AD 1490/~85 cm), which indicated a decrease in fire activity (Figure 2.5). A relatively small increase in CHAR (~5 # pieces/cm^2/yr) above background CHAR was recorded at ~460 cal yr BP (~AD 1490/~85 cm) (Figure 2.5), which marked a rise in fire activity and directly preceded the base of ecological zone WP-4 (Figure 2.4). CHAR declined below background CHAR for the remainder of the fire reconstruction, with the exception of small increases at ~300 cal yr BP (~AD 1650/~59 cm), ~140 cal yr BP (~AD 1810/~34 cm) at the end of ecological zone WP-4 (Figure 2.4), and at ~60 cal yr BP (~AD 1890/~21 cm). These three most recent increases in fire activity each had CHAR values of ≤ ~3 # pieces/cm^2/yr (Figure 2.5).

Stable isotope results

A heavy $\delta^{18}O$ value (~2.5 ‰) was recorded at ~4,831 cal yr BP (~2,881 BC/~350 cm), which suggested high evaporation-precipitation ratios (E/P) and increased aridity (Figure 2.6). Periods of high aridity result in the preferential evaporation of the lighter oxygen isotope, ^{16}O, therefore enriching lake waters in heavy oxygen (^{18}O). Ostracods incorporate oxygen from their host lake waters into their calcite shells, and as a consequence, geochemical analyses of ostracod carapaces preserved in lake sediments provide insight into shifts in the E/P balance of shallow lakes (Hodell et al., 1991 and 1995). $\delta^{18}O$ subsequently declined to lighter values between ~ -3 ‰ and ~ -3.2 ‰ from ~1,276 cal yr BP (~AD 674/~200 cm) to ~1,063 cal yr BP (~AD 887/~180 cm), with the exception of a brief rise in $\delta^{18}O$ to ~ -0.6 ‰ at ~1,153 cal yr BP (~AD 797/~190 cm) (Figure 2.6). Despite the intervening increase in $\delta^{18}O$ at ~1,153 cal yr BP, the period from

~1,276 cal yr BP to ~1,063 cal yr BP marked the interval with the lightest $\delta^{18}O$ values in our record, which indicated that E/P ratios were lower, and aridity decreased during that period. $\delta^{18}O$ increased abruptly between ~1,063 cal yr BP and ~933 cal yr BP (~AD 1017/~160 cm) to a value of ~2.4 ‰, which indicated an increase in E/P ratios and more arid climates (Figure 2.6). $\delta^{18}O$ values then declined sharply between ~933 cal yr BP and ~743 cal yr BP (~AD 1207/~130 cm) to ~ -1.7 ‰, which suggested the development of more mesic climates with lower E/P ratios (Figure 2.6). $\delta^{18}O$ subsequently increased between ~743 cal yr BP and ~615 cal yr BP (~AD 1335/~110 cm) to ~0.1 ‰, which suggested increasing E/P ratios and a relative rise in aridity (Figure 2.6). $\delta^{18}O$ exhibited less variability between ~615 cal yr BP and the core top (modern), as values fluctuated between ~0.9 ‰ and ~ -0.8 ‰ (Figure 2.6). Nonetheless, the majority of the $\delta^{18}O$ values in this interval (~615 cal yr BP-modern) were positive, which indicated that the late Holocene was characterized by relatively dry climates with a high E/P ratio (Figure 2.6). There were two exceptions to the observed pattern of late Holocene climatic stability—a sharp increase in $\delta^{18}O$ to ~2.1 ‰ at ~303 cal yr BP (~AD 1647/~60 cm), which indicated an increase in E/P ratios and high aridity, and a decline in $\delta^{18}O$ to ~ -1.2 ‰ at 115 cal yr BP (~AD 1835/~30 cm), which suggested that climates were wetter with lower E/P ratios (Figure 2.6).

The $\delta^{13}C$ isotopic curve largely parallels the patterns observed in the $\delta^{18}O$ isotopic curve (Figure 2.6), therefore suggesting a relationship between both isotopic systems. Photosynthesizing organisms inhabiting lakes preferentially uptake the lighter carbon isotope, ^{12}C, for use in biochemical processes, thus enriching lake waters in heavy carbon (^{13}C) (Caporaletti, 2011; Leng and Marshall, 2004). Consequently, increased periods of productivity result in enhanced uptake of ^{12}C and higher ^{13}C values (Caporaletti, 2011; Leng and Marshall, 2004). High aridity leads to an increase in E/P ratios and lake level decline. This hydrologic

scenario also results in the enrichment of lake waters in heavy oxygen (^{18}O) as light oxygen (^{16}O) preferentially evaporates. Ceteris paribus, shallow lakes are more productive than deeper lakes (Nixdorf and Deneke, 1997; Hupfer et al., 2008; Kilham and Kilham, 1990). It is therefore expected that as lake levels decline under high evaporation conditions, increases in measured ostracod ^{18}O values will be mirrored by increases in ostracod ^{13}C values, due to enhanced primary productivity and assimilation of ^{12}C (Li and Ku, 1997; Heaton et al., 1995). A high (positive) $\delta^{13}C$ value (~0.7 ‰) was recorded at ~4,831 cal yr BP (~2,881 BC/~350 cm), which suggested lake level decline and an increase in photosynthetic uptake of ^{12}C (Figure 2.6). $\delta^{13}C$ subsequently declined to between ~ -7.5 ‰ and ~ -9 ‰ from ~1,276 cal yr BP (~AD 674/~200 cm) to ~1,063 cal yr BP (~AD 887/~180 cm), which indicated that lake levels increased, and primary production fell (Figure 2.6). $\delta^{13}C$ then increased sharply to ~1.5 ‰ between ~1,063 cal yr BP and ~933 cal yr BP (~AD 1017/~160 cm), and then declined to ~ -2.7 ‰ between ~933 cal yr BP and ~743 cal yr BP (~AD 1207/~130 cm) (Figure 2.6). This observed abrupt increase and subsequent decline in $\delta^{13}C$ values indicated a rapid shift from shallow eutrophic lake conditions to a deeper, less productive lake environment. $\delta^{13}C$ subsequently increased to the highest value in the record (~2.5 ‰) between ~743 cal yr BP (~AD 1207/~130 cm) and ~491 cal yr BP (~AD 1459/~90 cm), which suggested lake level decline and an increase in primary productivity (Figure 2.6). $\delta^{13}C$ values then decreased gradually towards the core top (modern) to a value of ~ -2.5 ‰, which indicated an increase in lake levels and decline in primary productivity (Figure 2.6). Uncoupling between the observed timing or magnitude of shifts between the $\delta^{18}O$ and $\delta^{13}C$ records could be due to several factors. The release of ^{12}C-enriched carbon due to respiration and the decomposition of high quantities of organic material can lower $\delta^{13}C$ values (Heaton et al., 1995; Oana and Deevey, 1960). Similarly, groundwater inputs influenced by exchanges with

soils that have a high ^{12}C content due to the breakdown of soil organic matter can cause a decrease in lake $\delta^{13}C$ values (Leng and Marshall, 2004)—however, our coring site (Figure 2.2) was not located close to the springs that feed Wallywash Pond (Street-Perrott et al., 1993).

Discussion

Our study provides the first multi-proxy paleoecological record for Jamaica, W.I. that investigates millennial-scale environmental variability in the context of both human occupation and climate changes. Furthermore, the suite of biological and geochemical proxies used—pollen, charcoal, dung fungal spores (*Sporormiella*, *Cercophora* and *Sordaria*), and stable oxygen and carbon isotopes—enable us to make rigorous inferences about the island's environmental history that could not be drawn with the use of a single proxy. Successive periods of human occupation of Jamaica ranging from prehistoric to modern times were associated with vegetation changes and shifts in fire activity in our paleoecological reconstruction. Consequently, we provide sedimentary evidence of human-landscape interactions that pre-date historical archives and add valuable ecological and climatic context to previous archaeological investigations. Our paleoecological record also illuminates environmental conditions in Jamaica during past abrupt climate change events, including the Maya drought, which is widely hypothesized to have resulted in the collapse of the ancient Maya civilization (Peterson and Haug, 2005; Douglas et al., 2016), Medieval Warm Period and the Little Ice Age.

The first increase in fire activity in our charcoal record at ~1,370 cal yr BP (~AD 580) (Figure 2.5) approximates the established date of first human arrival in Jamaica. Archaeological records indicate that the Ostionoid peoples first settled on the island at ~1,300 cal yr BP (~AD 650) (Rouse, 1992). This initial surge in fire activity was followed by a period of sustained and intense landscape burning between ~1290 cal yr BP (~AD 660) and ~1160 cal yr BP (~AD 790)

(Figure 2.5). This period of enhanced fire regimes coincided with a decline in trees and shrubs and an increase in ruderal plant taxa, such as *Amaranthaceae* and *Asteraceae* (Zone WP-2, Figure 2.4), which are indicators of disturbance and are frequently associated with land clearance, agricultural intensification and human fire use (Clement and Horn, 2001; Mcandrews, 1988). Stratigraphic indicators of anthropogenic activity have been used to probe and revise histories of human settlement in a variety of geographic contexts, and the colonization of tropical islands has been a subject of particular interest (Burney, 1997; Kirch and Ellison, 1994; Siegel et al., 2015). The identified shifts in fire activity and vegetation associated with arrival of the Ostionoid peoples were coeval with a period of wetter climates between ~1,276 cal yr BP (~AD 674/~200 cm) to ~1,063 cal yr BP (~AD 887/~180 cm); however, this mesic interval was bisected by a period of relatively dry climate at ~1,153 cal yr BP (~AD 797/~190 cm) (Figure 2.6). Wetter climates could have contributed to a rise in fire activity by increasing available fuel loads for burning during seasonal dry periods, while more arid climates would have desiccated vegetation, thus making the landscape more prone to ignition. It is likely that both prehistoric human activity and prevailing climatic conditions were responsible for the observed increases in fire regimes during the interval between ~1290 cal yr BP (~AD 660) and ~1160 cal yr BP (~AD 790), however further study is warranted to determine the relative roles of natural versus human forcing. Nonetheless, the detection of a large increase in sedimentary charcoal fragments coupled with a decline in arboreal pollen and increase in the pollen of ruderal species is consistent with the impacts associated with first human colonization of a region (Dubois et al., 2018; Burney, 1997).

Basal ecological zone, WP-1 (1,594 cal yr BP-1,378 cal yr BP) (Figure 2.4), was dominated by mangrove-fern swamp vegetation, and *Conocarpus erectus* (Buttonwood

mangrove), *Polypodiaceae* (common ferns), *Cyperaceae*, *Acrostichum aureum* (Mangrove fern), *Rhizophora mangle* (Red mangrove), and *Grias cauliflora* (Anchovy pear) were characteristic of this ecological community. After the period of increased fire activity (~1290 cal yr BP- ~1160 cal yr BP) coinciding with ecological zone, WP-2 (Figure 2.4), vegetation shifted from dominance by herbaceous disturbance taxa to an open, early successional forest characterized primarily by the pioneer trees *Trema* and *Cecropia*. The mangrove-fern vegetation community did not return directly after the high-intensity disturbance event, and for the remainder of the vegetation record, the characteristic group of taxa never reassembled at the abundances observed in ecological zone, WP-1. The period directly after the interval of enhanced fire regimes was increasingly arid and may have been unfavorable for re-establishment of the mangrove-fern vegetation community. Failure of the mangrove-fern vegetation community to reorganize could have also been linked to the human presence on the landscape and exploitation. Regardless of the underlying factors that caused the mangrove-fern vegetation community to fail to re-establish, this observation highlights the sensitivity of these communities to ecological disturbance. Mangroves provide a diversity of ecosystem goods and services to humans, including coastal protection, carbon sequestration, and the provision of habitat for juvenile fish and shellfish (Lee et al., 2014; Ewel et al., 1998; Donato et al., 2011). Paleoecological data can provide valuable insight into the ecological resilience of plant taxa, including information about their responses to environmental stressors of varying magnitudes, and their population abundances over space and time.

Sedimentary evidence associated with the occupation of Jamaica by the Meillacan peoples, Taino culture, and European colonists was recorded in our paleoecological reconstruction. The Meillacan peoples colonized Jamaica at ~1,050 cal yr BP (~AD 900)

(Atkinson, 2006). There was a sharp increase in fire activity at ~1050 cal yr BP (Figure 2.5) that coincided with the arrival of the Meillacan peoples to the island. The Taino culture developed on the island at ~750 cal yr BP (~AD 1200) (Atkinson, 2006), and persisted until the arrival of Spanish colonists at ~456 cal yr BP (~AD 1494) (Atkinson, 2006). Increases in fire activity above background levels were recorded at ~740 cal yr BP (~AD 1210) and ~460 cal yr BP (~AD 1490) (Figure 2.5). These increases in fire activity were comparatively modest in size relative to the earlier surges associated with the arrival of the Ostionoid and Meillacan peoples; nonetheless, they are attributed to arrival of the Taino peoples and Spanish colonists to the island. Consequently, our sedimentary charcoal record documents the arrival of four successive groups to Jamaica, including the prehistoric cultural transitions of the Ostionoid, Meillacan and Taino peoples and the late 15th century colonization by the Spanish.

Of particular interest is the differences in magnitude between the earlier increases in fire activity associated with the Ostionoid and Meillacan peoples and the latter modest surges that coincide with arrival of the Taino peoples and Europeans. This observation can also be extended to analysis of the modern period of the charcoal record, where contemporary populations on the island undoubtedly use fire in the present-day, yet there is a conspicuous absence of large rises in fire activity during this interval. Burney et al. (1994) noted a similar trend in their charcoal reconstruction from Puerto Rico and other available records from Madagascar (Burney, 1987; Burney, 1993), where there appears to be no fire activity, then a very large increase in sustained fire activity associated with first human arrival, which is subsequently followed by a decline to levels which suggests a near absence of fire incidence. Burney et al. (1994) postulated that this trend may be due to changes in human population densities and organization on the landscape, in conjunction with shifts in resource exploitation patterns and land use. The arrival of Europeans

on the island coincided with the base of ecological zone, WP-4 (Figure 2.4). This ecological zone was characterized by the gradual decline of trees and shrubs, proliferation of grasses, consistent presence of ruderal plant species, appearance of cultivated species—most notably, *Saccharum officinarum* (Sugarcane), the primary export crop grown during the colonial period—and high abundances of *Sporormiella*, *Cercophora* and *Sordaria*. These palynological observations are consistent with the historical record of the Jamaican colonial period, which was marked by widespread land clearance for the establishment of up to hundreds of plantations, and intensification of crop and livestock agriculture (Higman, 2001).

Our paleoecological reconstruction provides insight into environmental conditions in Jamaica during past major abrupt climate events. The Maya Drought (~1,200 cal yr BP to ~1,000 cal yr BP) (Gill et al., 2007) was associated with a large spike in $\delta^{18}O$ and $\delta^{13}C$ values in our stable isotope record (194 cm to 170 cm), which indicated high aridity and lake level declines (Figure 2.6). The Medieval Warm Period (~1150 cal yr BP to ~650 cal yr BP) was associated with a large increase in $\delta^{18}O$ and $\delta^{13}C$ values in our stable isotope record, and then a subsequent gradual decline in $\delta^{18}O$ and $\delta^{13}C$ values for most of its extent (190 cm to 115 cm) (Figure 2.6). These shifts indicated that the period was first characterized by arid climates but became increasingly wet for the majority of the interval. Several circum-Caribbean records indicate that the Medieval Warm Period was wet and humid in the Caribbean (Lane et al., 2009; Carrillo-Bastos et al., 2010; Aragón-Moreno et al., 2012), therefore the prevailing trend towards mesic climates in our record further suggests regional coherence. The Little Ice Age (~550 cal yr BP to ~150 cal yr BP) was marked by positive $\delta^{18}O$ values and a conspicuous spike in $\delta^{18}O$ towards the end of the interval, which indicated arid climates (100 cm to 36 cm). $\delta^{13}C$ was slightly uncoupled from $\delta^{18}O$ during the recent Holocene and showed a negative trend towards the core top, which

indicated lake level increases. However, the highest value in the $\delta^{13}C$ record was recorded during this interval (~90 cm), which indicated lake level decline and dry climatic conditions (Figure 2.6). Taken together, both records indicated that the Little Ice Age was marked by arid climates in Jamaica, which is in agreement with other regional climate records (Lane et al., 2009; Burn and Palmer, 2014).

Conclusions

Our novel multi-proxy paleoecological reconstruction documents climate, ecological, and anthropogenic changes in Jamaica, West Indies from the mid-Holocene (~5,800 cal yr BP) to recent times. Four successive periods of human colonization and cultural shifts were documented in our sedimentary record, including the arrival of the Ostionoid peoples, the first group to colonize the island. First human arrival was coeval with a period of intensified fire activity and large vegetation changes, including the loss of a swamp mangrove-fern community which failed to re-establish after disturbance. Subsequent waves of colonization by the Meillacan peoples, Taino, and Europeans were associated with increases in fire activity above background levels. The period of European settlement was associated with declines in arboreal taxa, the appearance of cultivated species, high abundances of ruderal herbaceous taxa and an increase in dung fungal spores; thus reflecting historical documentation of extensive human landscape impacts during this interval. The Maya Drought coincided with arid conditions in Jamaica, while the Medieval Warm Period and Little Ice Age were represented by wet and dry climates respectively. These local observations are in agreement with previous circum-Caribbean studies, therefore supporting the notion of regional climate coherence during these periods of abrupt climate change.

References

Allison, R.T., 1999. Haematoxylin--from the wood. *Journal of Clinical Pathology* 52(7): 527.

Álvarez-Berríos, N.L., Redo, D.J., Aide, T.M., Clark, M.L. and Grau, R. 2013. Land Change in the Greater Antilles between 2001 and 2010. *Land* 2(2): 81-107.

Aragón-Moreno, A.A., Islebe, G.A. and Torrescano-Valle, N. 2012. A~3800-yr, high-resolution record of vegetation and climate change on the north coast of the Yucatan Peninsula. *Review of Palaeobotany and Palynology* 178: 35-42.

Bain, A., Faucher, A.M., Kennedy, L.M., LeBlanc, A.R., Burn, M.J., Boger, R. and Perdikaris, S. 2018. Landscape Transformation During Ceramic Age and Colonial Occupations of Barbuda, West Indies. *Environmental Archaeology* 23(1): 36-46.

Bakker, E.S., Sarneel, J.M., Gulati, R.D., Liu, Z. and van Donk, E. 2013. Restoring macrophyte diversity in shallow temperate lakes: biotic versus abiotic constraints. *Hydrobiologia* 710(1): 23-37.

Beckford, C., Barker, D. and Bailey, S. 2007. Adaptation, innovation and domestic food production in Jamaica: Some examples of survival strategies of small-scale farmers. *Singapore Journal of Tropical Geography* 28(3): 273-286.

Bender, M.A., Knutson, T.R., Tuleya, R.E., Sirutis, J.J., Vecchi, G.A., Garner, S.T. and Held, I.M. 2010. Modeled impact of anthropogenic warming on the frequency of intense Atlantic hurricanes. *Science* 327(5964): 454-458.

Benford, B., Tikoff, B. and DeMets, C. 2015. Interaction of reactivated faults within a restraining bend: Neotectonic deformation of southwest Jamaica. *Lithosphere* 7(1): 21-39.

Birks, J.S. and Barnes, R.D. 1990. Provenance variation in Pinus caribaea, P. oocarpa and P. patula ssp. tecunumanii. Oxford Forestry Institute, University of Oxford.

Blaauw, M., Christen, J.A. 2011. Flexible paleoclimate age-depth models using an autoregressive gamma process. *Bayesian Analysis* 6(3): 457-474.

Brokaw, N.V.L. 1987. Gap-phase regeneration of three pioneer tree species in a tropical forest. *The Journal of Ecology*: 9-19.

Burn, M.J. and Palmer, S.E. 2014. Solar forcing of Caribbean drought events during the last millennium. *Journal of Quaternary Science* 29(8): 827-836.

Burney, D.A. 1987a. Pre-settlement vegetation changes at Lake Tritrivakely, Madagascar. *Palaeoecology of Africa* 18: 357-381.

Burney, D.A. 1993. Late Holocene environmental changes in arid southwestern Madagascar. *Quaternary Research* 40(1): 98-106.

Burney, D.A. 1997. Tropical islands as paleoecological laboratories: gauging the consequences of human arrival. *Human Ecology* 25(3): 437-457.

Burney, D.A., Burney, L.P. and MacPhee, R.D. 1994. Holocene charcoal stratigraphy from Laguna Tortuguero, Puerto Rico, and the timing of human arrival on the island. *Journal of Archaeological Science* 21(2): 273-281.

Campbell, D., Barker, D. and McGregor, D. 2011. Dealing with drought: Small farmers and environmental hazards in southern St. Elizabeth, Jamaica. *Applied Geography* 31(1): 146-158.

Caporaletti, M. 2011. Ostracods and stable isotopes: proxies for palaeoenvironmental reconstructions. *Joannea--Geologie und Palaontologie* 11: 345.

Carrillo-Bastos, A., Islebe, G.A., Torrescano-Valle, N. and González, N.E. 2010. Holocene vegetation and climate history of central Quintana Roo, Yucatán Península, Mexico. *Review of Palaeobotany and Palynology* 160(3): 189-196.

Castilla-Beltrán, A., Hooghiemstra, H., Hoogland, M.L., Pagán-Jiménez, J., van Geel, B., Field, M.H., Prins, M., Donders, T., Malatesta, E.H., Hung, J.U. and McMichael, C.H. 2018. Columbus' footprint in Hispaniola: A paleoenvironmental record of indigenous and colonial impacts on the landscape of the central Cibao Valley, northern Dominican Republic. *Anthropocene* 22: 66-80.

Chen, A. and Taylor, M. 2008. "Enabling activities for the preparation of Jamaica's Second National Communication to the UNFCCC: climate scenarios for vulnerability and adaptation". Report by the Climate Studies Group Mona (CSGM), University of the West Indies, August 2008, Kingston, Jamaica.

Clement, R.M. and Horn, S.P. 2001. Pre-Columbian land-use history in Costa Rica: a 3000-year record of forest clearance, agriculture and fires from Laguna Zoncho. *The Holocene* 11(4): 419-426.

Colon, J.C.F. 1996. Phytogeographical trends, centers of high species richness and endemism, and the question of extinctions in the native flora of Puerto Rico. *Annals of the New York Academy of Sciences* 776(1): 89-102.

Cugny, C., Mazier, F. and Galop, D. 2010. Modern and fossil non-pollen palynomorphs from the Basque mountains (western Pyrenees, France): the use of coprophilous fungi to reconstruct pastoral activity. *Vegetation history and Archaeobotany* 19(5-6): 391-408.

Davis, S.D., Heywood, V.H., Herrera-MacBryde, O., Villa-Lobos, J. & Hamilton, A.C. (eds). 1997. Centres of Plant Diversity: A Guide and Strategy for their Conservation. Vol. 3: The Americas. IUCN Publications Unit, Gland, Switzerland.

De Vries, H. 1958. Atomic bomb effect: variation of radiocarbon in plants, shells, and snails in the past 4 years. *Science* 128: 250–251.

Dhar, T.K. and Khirfan, L. 2016. Community-based adaptation through ecological design: lessons from Negril, Jamaica. *Journal of Urban Design* 21(2): 234-255.

Digerfeldt, G. and Hendry, M.D. 1987. An 8000-year Holocene sea-level record from Jamaica: implications for interpretation of Caribbean reef and coastal history. *Coral Reefs* 5(4): 165-169.

Dirzo, R., Young, H.S., Mooney, H.A. and Ceballos, G. 2011. Seasonally dry tropical forests: ecology and conservation. Island Press.

Donato, D.C., Kauffman, J.B., Murdiyarso, D., Kurnianto, S., Stidham, M. and Kanninen, M. 2011. Mangroves among the most carbon-rich forests in the tropics. *Nature Geoscience* 4(5): 293.

Douglas, P.M., Demarest, A.A., Brenner, M. and Canuto, M.A. 2016. Impacts of climate change on the collapse of lowland Maya civilization. *Annual Review of Earth and Planetary Sciences* 44: 613-645.

Dubois, N., Saulnier-Talbot, É., Mills, K., Gell, P., Battarbee, R., Bennion, H., Chawchai, S., Dong, X., Francus, P., Flower, R. and Gomes, D.F. 2018. First human impacts and responses of aquatic systems: A review of palaeolimnological records from around the world. *The Anthropocene Review* 5(1): 28-68.

Duerden, J.E. 1895. Discovery of aboriginal Indian remains in Jamaica. *Nature* 52(1338): 173-174.

Dull, R.A. 2007. Evidence for forest clearance, agriculture, and human-induced erosion in Precolumbian El Salvador. *Annals of the Association of American Geographers* 97(1): 127-141.

Ehrhardt-Martinez, K. 1998. Social determinants of deforestation in developing countries: a cross-national study. *Social Forces* 77(2): 567-586.

Evelyn, O.B. and Camirand, R. 2003. Forest cover and deforestation in Jamaica: an analysis of forest cover estimates over time. *International Forestry Review* 5(4): 354-363.

Ewel, K., Twilley, R. and Ong, J.I.N. 1998. Different kinds of mangrove forests provide different goods and services. *Global Ecology & Biogeography Letters* 7(1): 83-94.

Eyre, L.A. 1986. Deforestation in Jamaica: its rate and implications. Department of Geology, University of the West Indies, Kingston: 29.

Eyre, L.A. 1987. Jamaica: a test case for tropical deforestation. *Ambio* 16(6): 336–343.

Eyre, L.A. 1996. The tropical rainforests of Jamaica. *Jamaica Journal* 26(1): 26–37.

Faegri, K. and Iverson, J. 1989. Textbook of Pollen Analysis, fourth ed. The Blackburn.

FAO. 2007. Mangroves of North and Central America 1980-2005, Country Reports. Forest Resources Assessment Programme, Working Paper 138 Rome, p. 86.

Fitzpatrick, S.M. 2013. Seafaring capabilities in the pre-Columbian Caribbean. *Journal of Maritime Archaeology* 8(1): 101-138.

Fujisaka, S., Escobar, G. and Veneklaas, E.J. 2000. Weedy fields and forests: interactions between land use and the composition of plant communities in the Peruvian Amazon. *Agriculture, Ecosystems & Environment* 78(2): 175-186.

Furtos, N.C. 1936. Fresh-water ostracoda from Florida and North Carolina. *American Midland Naturalist* 17(2): 491-522.

Gamble, D.W., Campbell, D., Allen, T.L., Barker, D., Curtis, S., McGregor, D. and Popke, J. 2010. Climate change, drought, and Jamaican agriculture: local knowledge and the climate record. *Annals of the Association of American Geographers* 100(4): 880-893.

Garrick, L.D. 1986. The Black River Lower Morass: A threatened wetland in Jamaica. *Oryx* 20(3): 155-160.

Gelorini, V., Verbeken, A., van Geel, B., Cocquyt, C. and Verschuren, D. 2011. Modern non-pollen palynomorphs from East African lake sediments. *Review of Palaeobotany and Palynology* 164(3-4): 143-173.

Gill, R.B., Mayewski, P.A., Nyberg, J., Haug, G.H. and Peterson, L.C. 2007. Drought and the Maya collapse. *Ancient Mesoamerica* 18(2): 283-302.

Grimm, Eric C. 1987. CONISS: a FORTRAN 77 program for stratigraphically constrained cluster analysis by the method of incremental sum of squares. *Computers & Geosciences* 13(1): 13-35.

Guernsey, J.E. 1941. A Climatic Map of Jamaica on the Köppen System. *Bulletin of the American Meteorological Society* 22(8): 327-331.

Heaton, T.H.E., Holmes, J.A. and Bridgwater, N.D. 1995. Carbon and oxygen isotope variations among lacustrine ostracods: implications for palaeoclimatic studies. *The Holocene* 5(4): 428-434.

Henry, C.S. 2018. Late pre-contact era Taíno subsistence economy and diet: Zooarchaeological perspectives from Maima (Doctoral dissertation, Environment: Department of Archaeology).

Higman, B.W. 2001. Jamaica surveyed: plantation maps and plans of the eighteenth and nineteenth centuries. University of West Indies Press.

Higuera-Gundy, A., Brenner, M., Hodell, D.A., Curtis, J.H., Leyden, B.W. and Binford, M.W. 1999. A 10,300 14 C yr record of climate and vegetation change from Haiti. *Quaternary Research* 52(2): 159-170.

Higuera, P.E., Brubaker, L.B., Anderson, P.M., Hu, F.S. and Brown, T.A. 2009. Vegetation mediated the impacts of postglacial climate change on fire regimes in the south-central Brooks Range, Alaska. *Ecological Monographs* 79(2): 201-219.

Higuera, P.E., Gavin, D.G., Bartlein, P.J. and Hallett, D.J. 2011. Peak detection in sediment–charcoal records: impacts of alternative data analysis methods on fire-history interpretations. *International Journal of Wildland Fire* 19(8): 996-1014.

Hodell, D.A., Curtis, J.H., Brenner, M. 1995. Possible role of climate in the collapse of Classic Maya civilization. *Nature* 375 (6530): 391–394.

Hodell, D.A., Curtis, J.H., Jones, G.A., Higuera-Gundy, A., Brenner, M., Binford, M.W. and Dorsey, K.T. 1991. Reconstruction of Caribbean climate change over the past 10,500 years. *Nature* 352(6338): 790-793.

Holmes, J.A. 1998. A late Quaternary ostracod record from Wallywash Great Pond, a Jamaican marl lake. *Journal of Paleolimnology* 19(2): 115-128.

Holmes, J.A., Street-Perrott, F.A., Ivanovich, M. and Perrott, R.A. 1995. A late Quaternary palaeolimnological record from Jamaica based on trace-element chemistry of ostracod shells. *Chemical Geology* 124(1-2): 143-160.

Hooghiemstra, H., Olijhoek, T., Hoogland, M., Prins, M., van Geel, B., Donders, T., Gosling, W. and Hofman, C. 2018. Columbus' environmental impact in the New World: Land use change in the Yaque River valley, Dominican Republic. *The Holocene* 28(11): 1818-1835.

Hupfer, M., Hilt, S., Jørgensen, S.E., Asolekar, S.R., Kalbar, P.P., Maillacheruvu, K.Y., Abell, R., Blanch, S., Thieme, M., Geller, W. and Koschorreck, M. 2008. Lake restoration p. 79.

Hyman, T.A. 2014. Assessing the vulnerability of beach tourism and non-beach tourism to climate change: a case study from Jamaica. *Journal of Sustainable Tourism* 22(8): 1197-1215.

Jamaica Meteorological Service. 2019. 20-year Mean Temperatures (1996-2015). Web. Accessed: April 10, 2019. URL: http://metservice.gov.jm/2017/06/11/20-year-mean-temperatures-1996-2015/

Jamaica Meteorological Service. 2019. 30-year Mean Rainfall by Station (in mm). Web. Accessed: April 10, 2019. URL: http://metservice.gov.jm/30-year-mean-rainfall-by-station-in-mm/

Janzen, D. 1988. Tropical dry forests. The most endangered major tropical ecosystem. Biodiversity (ed. by E.O. Wilson), pp. 130–137. National Academy of Sciences/Smithsonian Institution, Washington DC.

Kahr, B., Lovell, S. and Subramony, J.A. 1998. The progress of logwood extract. *Chirality: The Pharmacological, Biological, and Chemical Consequences of Molecular Asymmetry* 10(1-2): 66-77.

Keegan, W.F., Hofman, C.L. and Ramos, R.R. eds. 2013. "The Humanization of the Insular Caribbean", In The Oxford Handbook of Caribbean Archaeology. Oxford University Press. p. 129.

Kilham, P. and Kilham, S.S. 1990. OPINION Endless summer: internal loading processes dominate nutrient cycling in tropical lakes. *Freshwater Biology* 23(2): 379-389.

Kirch, P.V. and Ellison, J. 1994. Palaeoenvironmental evidence for human colonization of remote Oceanic islands. *Antiquity* 68(259): 310-321.

Knutson, T.R., McBride, J.L., Chan, J., Emanuel, K., Holland, G., Landsea, C., Held, I., Kossin, J.P., Srivastava, A.K. and Sugi, M. 2010. Tropical cyclones and climate change. *Nature Geoscience* 3(3): 157-163.

Kozlowski, J.K.1974. Preceramic cultures of the Caribbean. Uniwertytetu Jagiellonskiego, Kraków.

Kuhar, U., Germ, M., Gaberščik, A. and Urbanič, G. 2011. Development of a River Macrophyte Index (RMI) for assessing river ecological status. *Limnologica-Ecology and Management of Inland Waters* 41(3): 235-243.

Landsea, C.W. 1993. A climatology of intense (or major) Atlantic hurricanes. *Monthly Weather Review* 121(6): 1703-1713.

Lane, C.S., Horn, S.P., Mora, C.I. and Orvis, K.H. 2009. Late-Holocene paleoenvironmental change at mid-elevation on the Caribbean slope of the Cordillera Central, Dominican Republic: a multi-site, multi-proxy analysis. *Quaternary Science Reviews* 28(23): 2239-2260.

Last, W.M. (Eds.), Tracking Environmental Change Using Lake Sediments. Terrestrial, Algal, & Siliceous Indicators, vol. 3. Kluwer Academic Publishers, Dordrecht: 75e97.

LeBlanc, A.R., Kennedy, L.M., Liu, K.B. and Lane, C.S. 2017. Linking hurricane landfalls, precipitation variability, fires, and vegetation response over the past millennium from analysis of coastal lagoon sediments, southwestern Dominican Republic. *Journal of Paleolimnology* 58(2): 135-150.

Lee, S.Y., Primavera, J.H., Dahdouh-Guebas, F., McKee, K., Bosire, J.O., Cannicci, S., Diele, K., Fromard, F., Koedam, N., Marchand, C. and Mendelssohn, I. 2014. Ecological role and services of tropical mangrove ecosystems: a reassessment. *Global Ecology and Biogeography* 23(7): 726-743.

Leng, M.J. and Marshall, J.D. 2004. Palaeoclimate interpretation of stable isotope data from lake sediment archives. *Quaternary Science Reviews* 23(7-8): 811-831.

Li, H.C. and Ku, T.L. 1997. $\delta^{13}C$–$\delta^{18}C$ covariance as a paleohydrological indicator for closed-basin lakes. *Palaeogeography, Palaeoclimatology, Palaeoecology* 133(1-2): 69-80.

Liegel, L.H. 1991. Growth and site relationships of Pinus caribaea across the Caribbean Basin. Gen. Tech. Rep. SO-83. New Orleans, LA: US Dept of Agriculture, Forest Service, Southern Forest Experiment Station. 70 p., 83.

Lozano-García, M., Caballero, M., Ortega, B., Rodríguez, A. and Sosa, S. 2007. Tracing the effects of the Little Ice Age in the tropical lowlands of eastern Mesoamerica. *Proceedings of the National Academy of Sciences* 104(41): 16200-16203.

Lozano-García, S., Caballero, M., Ortega, B., Sosa, S., Rodríguez, A. and Schaaf, P. 2010. Late Holocene palaeoecology of Lago Verde: evidence of human impact and climate change in the northern limit of the neotropics during the late formative and classic periods. *Vegetation History and Archaeobotany* 19(3): 177-190.

Lucero, L.J. 2018. A Cosmology of Conservation in the Ancient Maya World. *Journal of Anthropological Research* 74(3): 327-359.

Lucero, L.J., Fletcher, R. and Coningham, R. 2015. From 'collapse' to urban diaspora: the transformation of low-density, dispersed agrarian urbanism. *Antiquity* 89(347): 1139-1154.

MacPhee, R.D.E. 2009. Insulae infortunatae: establishing a chronology for Late Quaternary mammal extinctions in the West Indies. In American megafaunal extinctions at the end of the Pleistocene (pp. 169-193). *Springer Netherlands*.

Mcandrews, J.H. 1988. Human disturbance of North American forests and grasslands: the fossil pollen record. In Vegetation history (pp. 673-697). Springer, Dordrecht.

McFarlane, D.A., Lundberg, J. and Fincham, A.G. 2002. A late Quaternary paleoecological record from caves of southern Jamaica, West Indies. *Journal of Cave and Karst Studies* 64(2): 117-125.

McSweeney, C., New, M., and Lizcano, G. 2008. UNDP Climate Change Country Profile Jamaica. Oxford, UK: School of Geography and Environment, University of Oxford.

Mickleburgh, H.L. and Pagán-Jiménez, J.R. 2012. New insights into the consumption of maize and other food plants in the pre-Columbian Caribbean from starch grains trapped in human dental calculus. *Journal of Archaeological Science* 39(7): 2468-2478.

Miles, L., Newton, A.C., DeFries, R.S., Ravilious, C., May, I., Blyth, S., Kapos, V. and Gordon, J.E. 2006. A global overview of the conservation status of tropical dry forests. *Journal of Biogeography* 33(3): 491-505.

Montenegro, R.A. and Stephens, C. 2006. Indigenous health in Latin America and the Caribbean. *The Lancet* 367(9525): 1859-1869.

Moore, C. 1991. Cabaret: Lithic workshop sites in Haiti. *Reports of the Archaeological-Anthropological Institute of the Netherlands Antilles* 9: 922–1004.

Morgan, G.S. 1993. Quaternary land vertebrates of Jamaica. *Geological Society of America Memoirs* 182: 417-442.

Mueller, J.R., Power, M.J. and Long, C.J. 2018. Climate and human influence on late Holocene fire regimes in the British Virgin Islands. *Quaternary Research*: 1-12.

Nakagawa, T. 2007. PolyCounter ver.1.0 & Ergodex DX-1: a cheap and very ergonomic electronic counter board system. *Quanternary International*: 167-168 Supplement, 298, doi:j.quaint.2007.04.001.

National Environment and Planning Agency. 2010. Summary of Jamaica's Third National Report to the Convention on Biological Diversity, 2003-2004. *NEPA*.

Nixdorf, B. and Deneke, R. 1997. Why'very shallow 'lakes are more successful opposing reduced nutrient loads. *Hydrobiologia* 342: 269-284.

Nkemdirim, L.C. 1979. Spatial and seasonal distribution of rainfall and runoff in Jamaica. *Geographical Review*: 288-301.

Nogué, S., de Nascimento, L., Froyd, C.A., Wilmshurst, J.M., de Boer, E.J., Coffey, E.E., Whittaker, R.J., Fernández-Palacios, J.M. and Willis, K.J. 2017. Island biodiversity conservation needs palaeoecology. *Nature Ecology & Evolution* 1(7), p.0181.

Nurse LA, McLean RF, Agard J, Briguglio LP, Duvat-Magnan V, Pelesikoti N, Tompkins E, Webb A. 2014. Small islands. In: Barros VR, Field CB, Dokken DJ, Mastrandrea MD, Mach KJ, Bilir TE, Chatterjee M, Ebi KL, Estrada YO, Genova RC, Girma B, Kissel ES, Levy AN, MacCracken S, Mastrandrea PR, White LL (eds) Climate change 2014: impacts, adaptation, and vulnerability. Part B: regional aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, pp 1613–1654.

Oana, S. and Deevey, E.S. 1960. Carbon 13 in lake waters and its possible bearing on paleolimnology. *American Journal of Science* 258-A: 253-272.

Parry, J.H. 1955. Plantation and provision ground: an historical sketch of the introduction of food crops into Jamaica. *Revista de historia de America* 39: 1-20.

Pearson, T.R., Burslem, D.F., Goeriz, R.E. and Dalling, J.W. 2003. Interactions of gap size and herbivory on establishment, growth and survival of three species of neotropical pioneer trees. *Journal of Ecology* 91(5): 785-796.

Pelaez, L.A.P., Moreno-Casasola, P. and Rosas, H.L. 2014. Hydrophyte composition of dune lakes and its relationship to land-use and water physicochemistry in Veracruz, Mexico. *Marine and Freshwater Research* 65(4): 312-326.

Pérez, L., Lorenschat, J., Brenner, M., Scharf, B. and Schwalb, A. 2010. Extant freshwater ostracodes (Crustacea: Ostracoda) from Lago Peten Itza, Guatemala. *Revista de Biología Tropical* 58(3): 871-895.

Peterson, L.C. and Haug, G.H. 2005. Climate and the collapse of Maya civilization: A series of multi-year droughts helped to doom an ancient culture. *American Scientist* 93(4): 322-329.

Portillo-Quintero, C.A. and Sánchez-Azofeifa, G.A. 2010. Extent and conservation of tropical dry forests in the Americas. *Biological Conservation* 143(1): 144-155.

R Development Core Team, 2013. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. ISBN 3-900051-07-0, URL http://www.r-project.org.

Rafter TA. and Fergusson GJ. 1957. Atom bomb effect–Recent increase of carbon-14 content of the atmosphere and biosphere. *Science* 126 (3273): 557-558.

Rashford, J. 1993. Arawak, Spanish and African contributions to Jamaica's settlement vegetation. *Jamaica Journal* 24(3): 17-23.

Reimer, P.J., Baillie, M.G., Bard, E., Bayliss, A., Beck, J.W., Blackwell, P.G., Ramsey, C.B., Buck, C.E., Burr, G.S., Edwards, R.L. and Friedrich, M. 2009. IntCal09 and Marine09 radiocarbon age calibration curves, 0–50,000 years cal BP. *Radiocarbon* 51(4): 1111-1150.

Renny, R. 1807. An History of Jamaica: With Observations on the Climate, Scenery, Trade, Productions, Negroes, Slave Trade, Diseases of Europeans, Customs, Manners, And Dispositions of the Inhabitants: to which is Added, an Illustration of the Advantages which are Likely to Result from the Abolition of the Slave Trade. J. Cawthorn.

Robach, F., Thiébaut, G., Trémolières, M. and Muller, S. 1996. A reference system for continental running waters: plant communities as bioindicators of increasing eutrophication in alkaline and acidic waters in north-east France. *Hydrobiologia* 340(1-3): 67-76.

Rodríguez, M. 1999. Excavations at Maruca, a Preceramic site in southern Puerto Rico. In: Winter JH (ed) *Proceedings of the Seventeenth Congress of the International Association for Caribbean Archaeology*. Molloy College, Rockville Centre, New York: 166–180.

Rosenmeier, M.F., Hodell, D.A., Brenner, M., Curtis, J.H. and Guilderson, T.P. 2002. A 4000-year lacustrine record of environmental change in the southern Maya lowlands, Peten, Guatemala. *Quaternary Research* 57(2): 183-190.

Roubik DW. and Moreno JE. 1991. Pollen and spores of Barro Colorado Island. Missouri Botanical Garden 36: 270 pp.

Rouse, I. 1992. The Tainos: rise and decline of the people who greeted Columbus. *Yale University Press*.

Royer, A. Malaizé, B., Lécuyer, C., Queffelec, A., Charlier, K., Caley, T. and Lenoble, A. 2017. A high-resolution temporal record of environmental changes in the Eastern Caribbean (Guadeloupe) from 40 to 10 ka BP. *Quaternary Science Reviews* 155: 198-212.

Satchell, V.M. 1990. From plots to plantations: land transactions in Jamaica, 1866–1900. Institute of Social and Economic Research, University of the West Indies, Kingston: 197.

Selvaraju, R., Trapido, P.J., Santos, N., Del Mar Polo Lacasa, M. and Hayman, A.A. 2013. Climate change and agriculture in Jamaica: Agricultural sector support analysis. FAO.

Sheridan, R.B. 1989. Changing Sugar Technology and the Labour Nexus in the British Caribbean, 1750-1900, with Special Reference to Barbados and Jamaica. *New West Indian Guide* 63(1/2): 59-93.

Siegel, P.E., Jones, J.G., Pearsall, D.M., Dunning, N.P., Farrell, P., Duncan, N.A., Curtis, J.H. and Singh, S.K. 2015. Paleoenvironmental evidence for first human colonization of the eastern Caribbean. *Quaternary Science Reviews* 129: 275-295.

Sivaram, P. 2013. Pollen morphology of selected bee forage plants. *Global Journal of Bio-Science and Biotechnology* 2(01): 82-90.

Street-Perrott, F.A., Hales, P.E., Perrott, R.A., Fontes, J.C., Switsur, V.R. and Pearson, A. 1993. Late Quaternary palaeolimnology of a tropical marl lake: Wallywash Great Pond, Jamaica. *Journal of Paleolimnology* 9(1): 3-22.

Stuiver, M. and Quay, P.D. 1980. Changes in atmospheric carbon-14 attributed to a variable sun. *Science* 207(4426): 11-19.

The World Bank. 2017. “Jamaica”. URL: https://data.worldbank.org/country/jamaica. Date accessed: April 10, 2019.

Tole, L. 2002. An estimate of forest cover extent and change in Jamaica using Landsat MSS data. *International Journal of Remote Sensing* 23(1): 91-106.

US Army Corps of Engineers. 2001. Water Resources Assessment of Jamaica. US Southern Command Mobile District and Topographic Engineering Center.

von Grafenstein, U., Erlernkeuser, H. and Trimborn, P. 1999. Oxygen and carbon isotopes in modern fresh-water ostracod valves: assessing vital offsets and autecological effects of interest for palaeoclimate studies. *Palaeogeography, Palaeoclimatology, Palaeoecology* 148(1): 133-152.

Wahl, D., Schreiner, T., Byrne, R. and Hansen, R. 2007. A paleoecological record from a Late Classic Maya reservoir in the north Petén. *Latin American Antiquity* 18(2): 212-222.

Waters, M.R., Giardino, J.R., Ryter, D.W. and Parrent, J.M. 1993. Geoarchaeological investigations of St. Ann's Bay, Jamaica: the search for the Columbus Caravels and an assessment of 1000 years of human land use. *Geoarchaeology* 8(4): 259-279.

Whitlock, C. and Larsen, C. 2001. Charcoal as a fire proxy. In: Smol, J.P., Birks, H.J.B.,

Willard, D.A., Bernhardt, C.E., Weimer, L., Cooper, S.R., Gamez, D. and Jensen, J. 2004. Atlas of pollen and spores of the Florida Everglades. *Palynology* 28(1): 175-227.

Wing, E.S. 2008. Pets and camp followers in the West Indies. In Case studies in environmental archaeology (pp. 405-425). Springer, New York, NY.

Woodward, R.P. 2006. Medieval legacies: the industrial archaeology of an early sixteenth century sugar mill at Sevilla la Nueva, Jamaica. Doctoral dissertation, Department of Archaeology-Simon Fraser University.

Table 2. 1 Wallywash Pond vegetation survey data.

Identified plant taxa from the upland, lowland, littoral and aquatic environments of Wallywash Pond. Plant taxa are characterized based on their cultivation (C=Cultivated, NC=Not cultivated) and endemic status (E=Endemic, NE=Not endemic), relative abundance as qualitatively estimated based on occurrences for individual taxa on the day of the vegetation survey (D=Dominant, A=Abundant, F=Frequent, O=Occasional, R=Rare), and affinity for dry limestone forest ecosystems (L=Characteristic of dry limestone forest ecosystems, NL=Not characteristic of dry limestone forest ecosystems).

Botanical Name	Common Name	Family	Cultivated	Endemic	Relative Abundance	Dry Limestone Forest
Abrus precatorius	John Crow Bead	Papilionaceae	NC	NE	R	L
Acacia farnesiana	-	Mimosaceae	NC	NE	O	L
Achyranthes indica	Devil's Horsewhip	Amaranthaceae	NC	NE	O	NL
Amaranthus dubius	Wild Callaloo	Amaranthaceae	NC	NE	R	NL
Ammannia sp.	-	Lythraceae	NC	NE	O	NL
Amyris plumieri	Candlewood	Rutaceae	NC	NE	R	L
Anacardium occidentalis	Cashew	Anacardiaceae	C	NE	R	NL
Andropogon bicornis	Foxtail Grass	Poaceae	NC	NE	O	NL
Andropogon pertusus	Seymour Grass	Poaceae	NC	NE	A	NL
Annona squamosa	Sweet Sop	Annonaceae	NC	NE	R	NL
Aristolochia littoralis	-	Aristolochiaceae	NC	NE	R	NL
Asplenium sp.	-	Polypodiaceae	NC	NE	R	NL
Azolla caroliniana	Mosquito Fern	Azollaceae	NC	NE	R	NL
Bourreria baccata	-	Boraginaceae	NC	NE	R	L
Bryophllum pinnatum	Leaf-of-Life	Crassulaceae	NC	NE	R	NL

Table 2.1. Continued.

Bucida buceras	Black Olive	Combretaceae	NC	NE	O	NL
Bumelia salicifolia	White Bullet	Sapotaceae	NC	NE	R	L
Bunchosia media	-	Malpighiaceae	NC	NE	R	L
Bursera simaruba	Red Birch	Burseraceae	NC	NE	R	L
Calotropis procera	Dumb Cotton	Asclepiadaceae	NC	NE	R	NL
Capsicum bacatum	Bird Pepper	Solanaceae	NC	NE	R	NL
Casearia guianensis	Wild Coffee	Flacourtiaceae	NC	NE	R	NL
Casearia hirsuta	Cloven Berries	Flacourtiaceae	NC	NE	R	L
Cassia emarginata	Senna Tree	Caesalpiniaceae	NC	NE	O	L
Centella asiatica	-	Ammiaceae	NC	NE	O	NL
Centrosema virginianum	-	Papilionaceae	NC	NE	R	NL
Chiococca alba	David's Root	Rubiaceae	NC	NE	R	L
Chloris inflata	-	Poaceae	NC	NE	O	NL
Cladium jamaicensis	Saw Grass	Cyperaceae	NC	NE	R	NL
Coccoloba sp.	-	Polygonaceae	NC	NE	R	L
Colubrina asiatica	Hoop Withe	Rhamnaceae	NC	NE	R	L
Commelina sp.	Water Grass	Commelinaceae	NC	NE	R	NL
Cordia globosa	Wild Sage	Boraginaceae	NC	NE	R	L
Crotalaria verrucosa	Blue Rattleweed	Papilionaceae	NC	NE	R	NL
Croton humilis	Pepper Rod	Euphorbiaceae	NC	NE	A	L
Croton linearis	Wild Rosemary	Euphorbiaceae	NC	NE	A	L
Cyperus ligularis	-	Cyperaceae	NC	NE	R	NL
Cyperus oxylepis	-	Cyperaceae	NC	NE	R	NL
Cyperus peruvianus	-	Cyperaceae	NC	NE	O	NL

Table 2.1. Continued.

Dendrophthora opuntoides	God Bush	Loranthaceae	NC	E	R	NL
Desmanthes sp.	Ground Tamarind	Mimosaceae	NC	NE	R	NL
Desmodium canum	Sweetheart	Papilionaceae	NC	NE	O	NL
Eleocharis elegans	-	Cyperaceae	NC	NE	O	NL
Euphorbia heterophylla	-	Euphorbiaceae	NC	NE	O	NL
Guazuma ulmifolia	Bastard Cedar	Sterculiaceae	NC	NE	O	NL
Haematoxylum campechianum	Logwood	Caesalpiniaceae	C	NE	O	L
Heliotropium angiospermum	Dog's Tail	Boraginaceae	NC	NE	O	NL
Indigofera suffruticosa	Wild Indigo	Papilionaceae	NC	NE	R	NL
Ipomoea aquatica	-	Convolvulaceae	NC	NE	R	NL
Ipomoea sp.	-	Convolvulaceae	NC	NE	O	NL
Jacaima costata	-	Asclepiadaceae	NC	E	R	L
Jatropha gossypiifolia	Bellyache Bush	Euphorbiaceae	NC	NE	R	NL
Laetia thamnia	Scarlet Seed	Flacourtiaceae	NC	NE	R	L
Lantana camara	Wild Sage	Verbenaceae	NC	NE	O	L
Lasciacis divaricata	-	Poaceae	NC	NE	R	L
Lemna sp.	Duck Weed	Lemnaceae	NC	NE	O	NL
Leptochloa domingensis	-	Poaceae	NC	NE	R	NL
Ludwigia peploides	-	Onagraceae	NC	NE	O	NL
Malpighia glabra	Wild Cherry	Malpighiaceae	NC	NE	R	L
Malvastrum americanum	-	Malvaceae	NC	NE	O	NL
Malvastrum coromandelianum	-	Malvaceae	NC	NE	O	NL
Melioccus bijugatus	Guinep	Sapindaceae	C	NE	R	NL
Melochia nodiflora	-	Sterculiaceae	NC	NE	O	NL

Table 2.1. Continued.

Mimosa pudica	Shame Weed	Mimosaceae	NC	NE	R	NL
Morinda royoc	Strongback	Rubiaceae	NC	NE	R	L
Nymphaea ampla	Water Lily	Nymphaeaeceae	NC	NE	O	NL
Ocimum gratissimum	African Tea Bush	Lamiaceae	NC	NE	O	NL
Oeceoclades maculata	African Orchid	Orchidaceae	NC	NE	R	L
Paspalum distichum	-	Poaceae	NC	NE	R	NL
Paullinia sp.	-	Sapindaceae	NC	NE	R	L
Phragmites australis	Reed	Poaceae	NC	NE	O	NL
Piscidia piscipula	Dogwood	Papilionaceae	NC	NE	O	L
Pisonea aculeata	Wait-a-bit	Nyctaginaceae	NC	NE	O	L
Pithecellobium unguis-cati	Bread –and-Cheese	Mimosaceae	NC	NE	R	L
Pluchea odorata	Bitter Tobacco	Asteraceae	NC	NE	R	NL
Plumbago scandens	Wild Plumbago	Plumbaginaceae	NC	NE	O	NL
Potamogeton nodosus	-	Potamogetaceae	NC	NE	F	NL
Priva lappulacea	Fasten-pon-Coat	Verbenaceae	NC	NE	O	NL
Prosopis juliflora	Cashew, Mesquite	Mimosaceae	NC	NE	O	NL
Randia aculeata	Box Briar	Rubiaceae	NC	NE	R	L
Rhyncheletrum repens	Natal Grass	Poaceae	NC	NE	R	NL
Rhynchosia phaseoloides	-	Papilionaceae	NC	NE	R	NL
Rivina humilis	Dogberry	Phytolaccaceae	NC	NE	R	NL
Ruellia tuberosa	Duppy Gun	Acanthaceae	NC	NE	R	NL
Sabal jamaicensis	Big/Bull Thatch	Arecaceae	NC	NE	R	NL
Sagittaria guayanensis	-	Alismataceae	NC	NE	F	NL

Table 2.1. Continued.

Samanea saman	Guango	Mimosaceae	NC	NE	O	NL
Scleria lithosperma	-	Cyperaceae	NC	NE	O	L
Sida acuta	Broom Weed	Malvaceae	NC	NE	F	NL
Sida procumbens	-	Malvaceae	NC	NE	R	NL
Simaruba glauca	Bitter Damson	Simaroubaceae	NC	NE	R	L
Solanum erianthum	Wild Susumber	Solanaceae	NC	NE	R	NL
Solanum mammosum	Cockroach Poison	Solanaceae	NC	NE	R	NL
Solanum torvum	Susumber	Solanaceae	NC	NE	O	NL
Spermacoce confusa	-	Rubiaceae	NC	NE	R	NL
Spilanthes urens	Pigeon Coop	Asteraceae	NC	NE	R	NL
Stachytarpheta jamaicensis	Vervaine	Verbenaceae	NC	NE	R	NL
Stylosanthes hamata	Donkey Weed	Papilionaceae	NC	NE	F	L
Tabernaemontana laurifolia	-	Apocynaceae	NC	NE	R	L
Tamarindus indica	Tamarind	Caesalpiniaceae	C	NE	R	NL
Tecoma stans	Yellow Elder	Bignoniaceae	NC	NE	R	L
Tragia volubilis	Twining Cowitch	Euphorbiaceae	NC	NE	R	L
Tridax procumbens	-	Asteraceae	NC	NE	R	NL
Trophis racemosa	-	Moraceae	NC	NE	R	NL
Typha domingensis	Reedmace	Typhaceae	NC	NE	A	NL
Urechites lutea	Nightshade	Apocynaceae	NC	NE	O	NL
Vernonia cinerea	-	Asteraceae	NC	NE	O	NL
Waltheria indica	Raichi	Sterculiaceae	NC	NE	O	NL
Wissadula sp.	-	Malvaceae	NC	NE	O	NL
Zanthoxylum martinicense	Prickly Yellow	Rutaceae	NC	NE	O	L

Table 2. 2 Radiocarbon dates obtained for WALL18.

Mean calibrated ages were generated using the Bacon program and the IntCal09 calibration curve (Blaauw and Christen, 2011).

Lab #	Depth (cm)	^{14}C age	1-σ	Mean calibrated age	Material
39643	182.75	800	25	1078	Macrocharcoal fragments
39644	198.25	510	25	1254[a]	Macrocharcoal fragments
39645	205.75	1300	30	1370	Macrocharcoal fragments

[a] This reported mean calibrated age was generated by the Bacon program for the associated sediment depth (198.25 cm) after omission of the related ^{14}C age. The ^{14}C age was omitted as a result of age reversal, which the Bacon program rejects when calculating age-depth models.

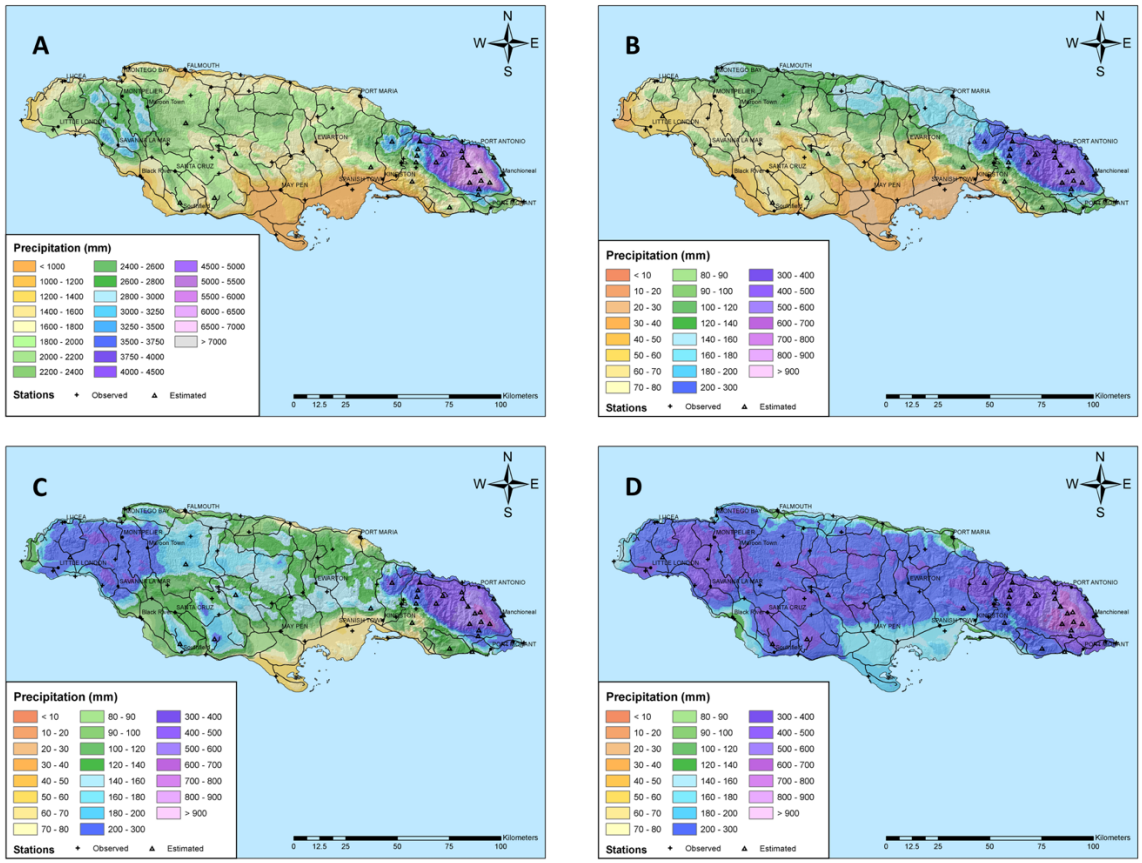

Figure 2. 1 Annual and seasonal precipitation patterns of Jamaica.

Average monthly precipitation for Jamaica for the period 1971-2000: A) Annual, B) January, C) June and D) October. The annual precipitation distribution (A) reflects the rain shadow effect of the central mountainous region, which results in high rainfall in the northeastern portion of the island and low rainfall in the leeward southern coastal plains. The seasonal precipitation distribution (B-D) reflects the annual cycle of rainfall on the island, where precipitation maxima coincide with northern displacement of the Intertropical Convergence Zone during boreal summer and peak activity of the North Atlantic hurricane season (August-October) (Copyright © 2019, PRISM Climate Group, Oregon State University, http://prism.oregonstate.edu, Map created April 24, 2019).

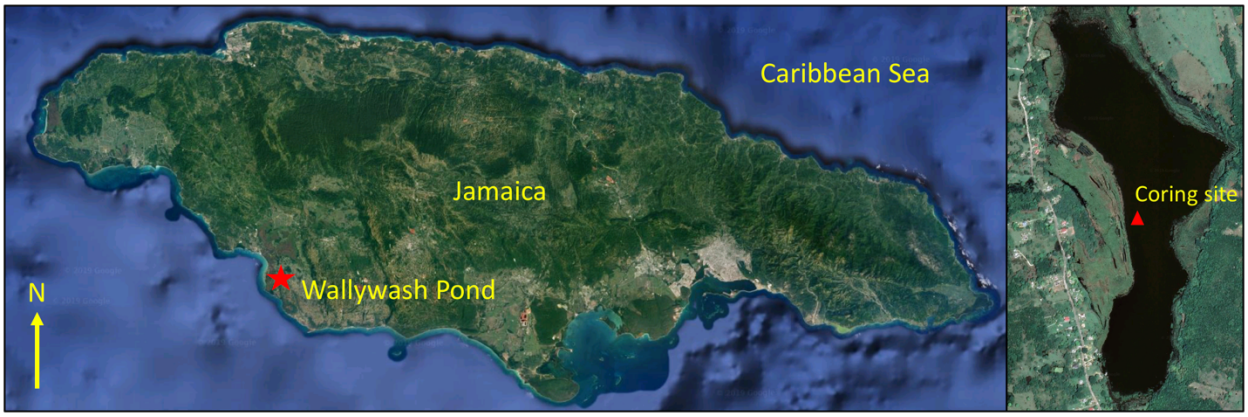

Figure 2. 2 Study location and coring site.

(L) Image of the island, Jamaica, indicating the geographical location of Wallywash Pond close to the southwestern coast (★). (R) Image of Wallywash Pond and the surrounding landscape, indicating the coring site close to the western shore of the lake (▲). Images collected from Google Earth (L: SIO, NOAA, U.S. Navy, NGA, GEBCO, Landsat/Copernicus 2019; R: CNES/Airbus 2019).

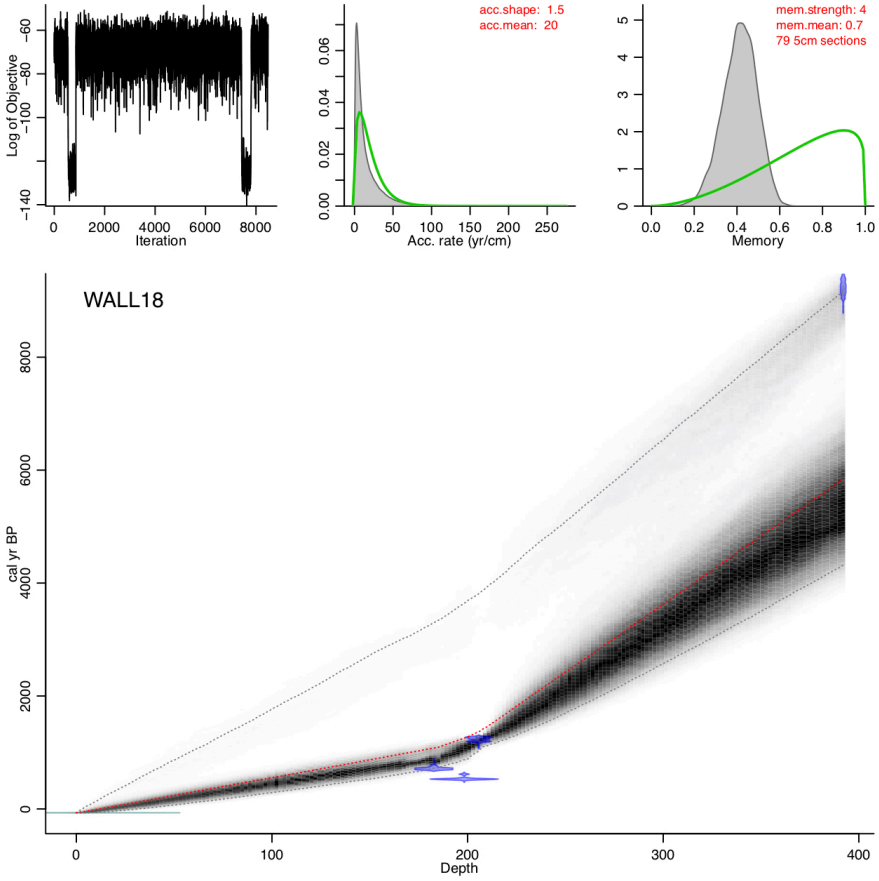

Figure 2. 3 Bayesian age-depth model made using Bacon software.

Upper panel: L) Markov Chain Monte Carlo iterations that calculate sedimentation rates, M) prior (lines) and post-analysis (area fills) estimates for sedimentation rates, and R) prior and post-analysis estimates for autocorrelation of sedimentation rates. The bottom panel shows the age-depth model with 95% CIs (dotted lines), probability distribution of calculated calibrated ^{14}C ages (gray fill, likelihood increases with darker color), and the calibrated dates used to construct the age-depth model (floating markers) (Blaauw and Christen, 2011).

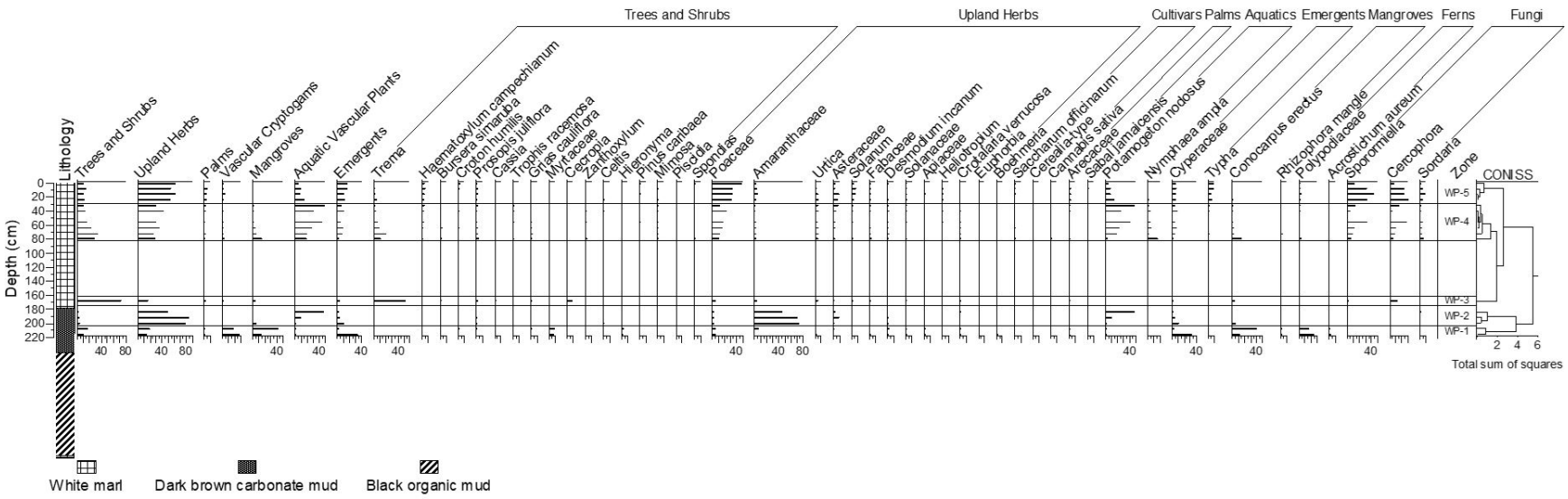

Figure 2. 4 Fossil pollen diagram for WALL18 and lithology.

Pollen abundances are represented as a percentage (%) of the terrestrial and aquatic pollen sum. Fungal spores were omitted from pollen sums for percentage calculations and are represented as abundance counts. CONISS analysis (far right) was performed using Tilia (Grimm, 1987) version 2.1.1 and ecological zonations (WP-1 to WP-5) are indicated by unbroken horizontal lines. WALL18 lithology (far left) was also compiled using Tilia software.

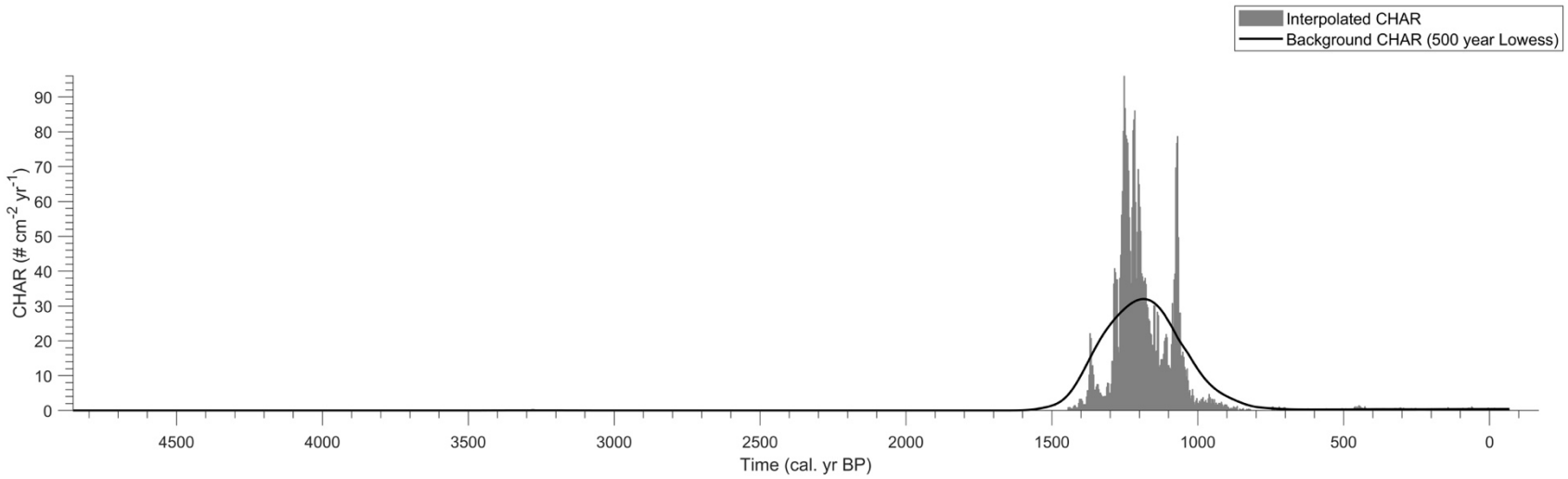

Figure 2. 5 Fire reconstruction for WALL18.

Fire activity represented as interpolated charcoal accumulation rates (Interpolated CHAR, gray fill) (number of charcoal pieces/cm^2/year). Low frequency background CHAR was estimated using a Lowess smoother with a 500-year smoothing window (solid line). Interpolated CHAR values greater than background CHAR levels indicate periods of increased fire activity. Interpolated CHAR and background CHAR values were calculated in Matlab using the CharAnalysis program version 1.1 (Higuera et al., 2009 and 2010).

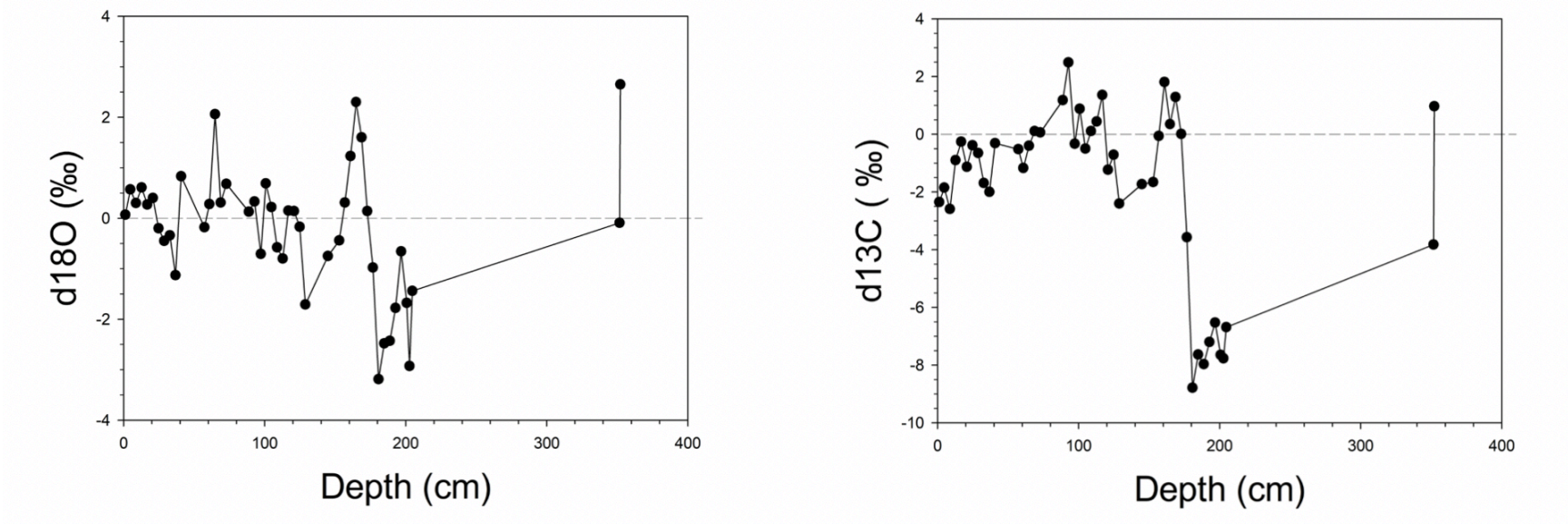

Figure 2. 6 Stable isotope curves for WALL18.

Stable isotope data were obtained from ≥ 10 ostracod valves or 5 intact ostracods of the species *Cypretta brevisaepta*. (L) Stable oxygen isotope values ($\Delta^{18}O$) represented as the ratio of $^{18}O/^{16}O$ (± 0.10, 1σ SD) relative to the VPDB standard. (R) Stable carbon isotope values ($\Delta^{13}C$) represented as the ratio of $^{13}C/^{12}C$ (± 0.08, 1σ SD) relative to the VPDB standard. Geochemical analyses were conducted at the University of Arizona Environmental Isotope Laboratory.

REFERENCES

Aimers, J.J. 2007. What Maya collapse? Terminal classic variation in the Maya lowlands. *Journal of Archaeological Research* 15(4): 329-377.

Ali, A.A., Higuera, P.E., Bergeron, Y. and Carcaillet, C. 2009. Comparing fire-history interpretations based on area, number and estimated volume of macroscopic charcoal in lake sediments. *Quaternary Research* 72(3): 462-468.

Allison, R.T., 1999. Haematoxylin--from the wood. *Journal of Clinical Pathology* 52(7): 527.

Álvarez-Berríos, N.L., Redo, D.J., Aide, T.M., Clark, M.L. and Grau, R. 2013. Land Change in the Greater Antilles between 2001 and 2010. *Land* 2(2): 81-107.

Ammann, B., Birks, H.J.B., Brooks, S.J., Eicher, U., von Grafenstein, U., Hofmann, W., Lemdahl, G., Schwander, J., Tobolski, K. and Wick, L. 2000. Quantification of biotic responses to rapid climatic changes around the Younger Dryas—a synthesis. *Palaeogeography, Palaeoclimatology, Palaeoecology* 159(3): 313-347.

Aragón-Moreno, A.A., Islebe, G.A. and Torrescano-Valle, N. 2012. A~3800-yr, high-resolution record of vegetation and climate change on the north coast of the Yucatan Peninsula. *Review of Palaeobotany and Palynology* 178: 35-42.

Bain, A., Faucher, A.M., Kennedy, L.M., LeBlanc, A.R., Burn, M.J., Boger, R. and Perdikaris, S. 2018. Landscape Transformation During Ceramic Age and Colonial Occupations of Barbuda, West Indies. *Environmental Archaeology* 23(1): 36-46.

Bakker, E.S., Sarneel, J.M., Gulati, R.D., Liu, Z. and van Donk, E. 2013. Restoring macrophyte diversity in shallow temperate lakes: biotic versus abiotic constraints. *Hydrobiologia* 710(1): 23-37.

Barker, D. 2012. Caribbean agriculture in a period of global change: vulnerabilities and opportunities. *Caribbean Studies* 40(2): 41-61.

Beckford, C., Barker, D. and Bailey, S. 2007. Adaptation, innovation and domestic food production in Jamaica: Some examples of survival strategies of small-scale farmers. *Singapore Journal of Tropical Geography* 28(3): 273-286.

Bellard, C., Leclerc, C. and Courchamp, F. 2014. Impact of sea level rise on the 10 insular biodiversity hotspots. *Global Ecology and Biogeography* 23(2): 203-212.

Bender, M.A., Knutson, T.R., Tuleya, R.E., Sirutis, J.J., Vecchi, G.A., Garner, S.T. and Held, I.M. 2010. Modeled impact of anthropogenic warming on the frequency of intense Atlantic hurricanes. *Science* 327(5964): 454-458.

Benford, B., Tikoff, B. and DeMets, C. 2015. Interaction of reactivated faults within a restraining bend: Neotectonic deformation of southwest Jamaica. *Lithosphere* 7(1): 21-39.

Bennett, K.D. and Willis, K.J. 2002. Pollen. In Tracking environmental change using lake sediments (pp. 5-32). Springer Netherlands.

Berchin, I.I., Valduga, I.B., Garcia, J. and de Andrade, J.B.S.O. 2017. Climate change and forced migrations: An effort towards recognizing climate refugees. *Geoforum* 84: 147-150.

Bigler, C. and Hall, R.I. 2002. Diatoms as indicators of climatic and limnological change in Swedish Lapland: a 100-lake calibration set and its validation for paleoecological reconstructions. *Journal of Paleolimnology* 27(1): 97-115.

Birks, H.H. and Birks, H.J.B. 2006. Multi-proxy studies in palaeolimnology. *Vegetation History and Archaeobotany* 15(4): 235-251.

Birks, H.J.B. and Birks, H.H. 2008. Biological responses to rapid climate change at the Younger Dryas—Holocene transition at Kråkenes, western Norway. *The Holocene* 18(1): 19-30.

Birks, J.S. and Barnes, R.D. 1990. Provenance variation in Pinus caribaea, P. oocarpa and P. patula ssp. tecunumanii. Oxford Forestry Institute, University of Oxford.

Blaauw, M., Christen, J.A. 2011. Flexible paleoclimate age-depth models using an autoregressive gamma process. *Bayesian Analysis* 6(3): 457-474.

Brenner, M., Hodell, D.A., Rosenmeier, M.F., Curtis, J.H., Binford, M.W. and Abbott, M.B. 2001. Abrupt climate change and pre-Columbian cultural collapse. In Interhemispheric climate linkages (pp. 87-103). Academic Press.

Brewbaker, J.L. 1979. Diseases of maize in the wet lowland tropics and the collapse of the Classic Maya civilization. *Economic Botany* 33(2): 101-118.

Brokaw, N.V.L. 1987. Gap-phase regeneration of three pioneer tree species in a tropical forest. *The Journal of Ecology*: 9-19.

Brooks, S.J. 2006. Fossil midges (Diptera: Chironomidae) as palaeoclimatic indicators for the Eurasian region. *Quaternary Science Reviews* 25(15): 1894-1910.

Brooks, T.M., Mittermeier, R.A., Mittermeier, C.G., Da Fonseca, G.A., Rylands, A.B., Konstant, W.R., Flick, P., Pilgrim, J., Oldfield, S., Magin, G. and Hilton-Taylor, C. 2002. Habitat loss and extinction in the hotspots of biodiversity. *Conservation Biology* 16(4): 909-923.

Buckley, B.M., Anchukaitis, K.J., Penny, D., Fletcher, R., Cook, E.R., Sano, M., Wichienkeeo, A., Minh, T.T. and Hong, T.M. 2010. Climate as a contributing factor in the demise of Angkor, Cambodia. *Proceedings of the National Academy of Sciences* 107(15): 6748-6752.

Burn, M.J. and Palmer, S.E. 2014. Solar forcing of Caribbean drought events during the last millennium. *Journal of Quaternary Science* 29(8): 827-836.

Burney, D.A. 1987. Pre-settlement vegetation changes at Lake Tritrivakely, Madagascar. *Palaeoecology of Africa* 18: 357-381.

Burney, D.A. 1993. Late Holocene environmental changes in arid southwestern Madagascar. *Quaternary Research* 40(1): 98-106.

Burney, D.A. 1997. Tropical islands as paleoecological laboratories: gauging the consequences of human arrival. *Human Ecology* 25(3): 437-457.

Burney, D.A., Burney, L.P. and MacPhee, R.D. 1994. Holocene charcoal stratigraphy from Laguna Tortuguero, Puerto Rico, and the timing of human arrival on the island. *Journal of Archaeological Science* 21(2): 273-281.

Burney, D.A., Robinson, G.S. and Burney, L.P. 2003. Sporormiella and the late Holocene extinctions in Madagascar. *Proceedings of the National Academy of Sciences* 100(19): 10800-10805.

Burney, L.P. and Burney, D.A. 2003. Charcoal stratigraphies for Kaua'i and the timing of human arrival. *Pacific Science* 57(2): 211-226.

Campbell, D., Barker, D. and McGregor, D. 2011. Dealing with drought: Small farmers and environmental hazards in southern St. Elizabeth, Jamaica. *Applied Geography* 31(1): 146-158.

Campbell, J.D., Taylor, M.A., Stephenson, T.S., Watson, R.A. and Whyte, F.S. 2011. Future climate of the Caribbean from a regional climate model. *International Journal of Climatology* 31(12): 1866-1878.

Caporaletti, M. 2011. Ostracods and stable isotopes: proxies for palaeoenvironmental reconstructions. *Joannea--Geologie und Palaontologie* 11: 345.

Carrillo-Bastos, A., Islebe, G.A., Torrescano-Valle, N. and González, N.E. 2010. Holocene vegetation and climate history of central Quintana Roo, Yucatán Península, Mexico. *Review of Palaeobotany and Palynology* 160(3): 189-196.

Castañeda, I.S. and Schouten, S. 2011. A review of molecular organic proxies for examining modern and ancient lacustrine environments. *Quaternary Science Reviews* 30(21): 2851-2891.

Castilla-Beltrán, A., Hooghiemstra, H., Hoogland, M.L., Pagán-Jiménez, J., van Geel, B., Field, M.H., Prins, M., Donders, T., Malatesta, E.H., Hung, J.U. and McMichael, C.H. 2018. Columbus' footprint in Hispaniola: A paleoenvironmental record of indigenous and colonial impacts on the landscape of the central Cibao Valley, northern Dominican Republic. *Anthropocene* 22: 66-80.

Chambers, F.M., Crowle, A., Daniell, J.R., Mauquoy, D., McCarroll, J., Sanderson, N., Thom, T., Toms, P. and Webb, J.C. 2017. Ascertaining the nature and timing of mire degradation: using palaeoecology to assist future conservation management in Northern England. *AIMS Environmental Science* 4(1): 54-82.

Chen, A. and Taylor, M. 2008. "Enabling activities for the preparation of Jamaica's Second National Communication to the UNFCCC: climate scenarios for vulnerability and adaptation". Report by the Climate Studies Group Mona (CSGM), University of the West Indies, August 2008, Kingston, Jamaica.

Chen, A.A. and Taylor, M.A. 2002. Investigating the link between early season Caribbean rainfall and the El Niño+ 1 year. *International Journal of Climatology* 22(1): 87-106.

Chiang, J.C. and Bitz, C.M. 2005. Influence of high latitude ice cover on the marine Intertropical Convergence Zone. *Climate Dynamics* 25(5): 477-496.

Chiang, J.C., Biasutti, M. and Battisti, D.S. 2003. Sensitivity of the Atlantic intertropical convergence zone to last glacial maximum boundary conditions. *Paleoceanography* 18(4).

Cincotta, R.P., Wisnewski, J. and Engelman, R. 2000. Human population in the biodiversity hotspots. *Nature* 404(6781): 990-992.

Clark, J.S., 1988. Particle motion and the theory of charcoal analysis: source area, transport, deposition, and sampling. *Quaternary Research* 30(1): 67-80.

Clement, R.M. and Horn, S.P. 2001. Pre-Columbian land-use history in Costa Rica: a 3000-year record of forest clearance, agriculture and fires from Laguna Zoncho. *The Holocene* 11(4): 419-426.

Cohen, A.S. 2017. The past is a key to the future: Lessons paleoecological data can provide for management of the African Great Lakes. *Journal of Great Lakes Research*. doi: https://doi.org/10.1016/j.jglr.2017.10.001

Colon, J.C.F. 1996. Phytogeographical trends, centers of high species richness and endemism, and the question of extinctions in the native flora of Puerto Rico. *Annals of the New York Academy of Sciences* 776(1): 89-102.

Constable, A.L. 2017. Climate change and migration in the Pacific: options for Tuvalu and the Marshall Islands. *Regional Environmental Change* 17(4): 1029-1038.

Cook, K.H. and Vizy, E.K. 2010. Hydrodynamics of the Caribbean low-level jet and its relationship to precipitation. *Journal of Climate* 23(6): 1477-1494.

Corlett, R.T. 2012. Climate change in the tropics: the end of the world as we know it?. *Biological Conservation* 151(1): 22-25.

Correa-Metrio, A., Bush, M.B., Hodell, D.A., Brenner, M., Escobar, J. and Guilderson, T. 2012. The influence of abrupt climate change on the ice-age vegetation of the Central American lowlands. *Journal of Biogeography* 39(3): 497-509.

Cugny, C., Mazier, F. and Galop, D. 2010. Modern and fossil non-pollen palynomorphs from the Basque mountains (western Pyrenees, France): the use of coprophilous fungi to reconstruct pastoral activity. *Vegetation history and Archaeobotany* 19(5-6): 391-408.

Daniau, A.L., Goñi, M.F.S., Martinez, P., Urrego, D.H., Bout-Roumazeilles, V., Desprat, S. and Marlon, J.R. 2013. Orbital-scale climate forcing of grassland burning in southern Africa. *Proceedings of the National Academy of Sciences* 110(13): 5069-5073.

Darrow, W.K. and Zanoni, T. 1990. Hispaniolan pine (*Pinus occidentalis* Swartz) a little known sub-tropical pine of economic potential. *The Commonwealth Forestry Review*: 133-146.

Dávalos, L.M. and Russell, A.L. 2012. Deglaciation explains bat extinction in the Caribbean. *Ecology and Evolution* 2(12): 3045-3051.

Dávalos, L.M. and Turvey, S.T. 2012. West Indian mammals: the old, the new, and the recently extinct. Bones, clones and biomes: the history and geography of recent neotropical mammals: 157-202.

Davis, M.B. 2000. Palynology after Y2K—understanding the source area of pollen in sediments. *Annual Review of Earth and Planetary Sciences* 28(1): 1-18.

Davis, M.B. and Shaw, R.G. 2001. Range shifts and adaptive responses to Quaternary climate change. *Science* 292(5517): 673-679.

Davis, O.K. 1987. Spores of the dung fungus *Sporormiella*: increased abundance in historic sediments and before Pleistocene megafaunal extinction. *Quaternary Research* 28(2): 290-294.

Davis, S.D., Heywood, V.H., Herrera-MacBryde, O., Villa-Lobos, J. & Hamilton, A.C. (eds). 1997. Centres of Plant Diversity: A Guide and Strategy for their Conservation. Vol. 3: The Americas. IUCN Publications Unit, Gland, Switzerland.

De Vries, H. 1958. Atomic bomb effect: variation of radiocarbon in plants, shells, and snails in the past 4 years. *Science* 128: 250–251.

Denis, E.H., Toney, J.L., Tarozo, R., Anderson, R.S., Roach, L.D. and Huang, Y. 2012. Polycyclic aromatic hydrocarbons (PAHs) in lake sediments record historic fire events: validation using HPLC-fluorescence detection. *Organic Geochemistry* 45: 7-17.

Deutsch, C.A., Tewksbury, J.J., Huey, R.B., Sheldon, K.S., Ghalambor, C.K., Haak, D.C. and Martin, P.R. 2008. Impacts of climate warming on terrestrial ectotherms across latitude. *Proceedings of the National Academy of Sciences* 105(18): 6668-6672.

Dhar, T.K. and Khirfan, L. 2016. Community-based adaptation through ecological design: lessons from Negril, Jamaica. *Journal of Urban Design* 21(2): 234-255.

Diamond, J. 2009. Archaeology: Maya, Khmer and Inca. *Nature* 461(7263): 479-480.

Digerfeldt, G. and Hendry, M.D. 1987. An 8000-year Holocene sea-level record from Jamaica: implications for interpretation of Caribbean reef and coastal history. *Coral Reefs* 5(4): 165-169.

Dirzo, R., Young, H.S., Mooney, H.A. and Ceballos, G. 2011. Seasonally dry tropical forests: ecology and conservation. Island Press.

Donato, D.C., Kauffman, J.B., Murdiyarso, D., Kurnianto, S., Stidham, M. and Kanninen, M. 2011. Mangroves among the most carbon-rich forests in the tropics. *Nature Geoscience* 4(5): 293.

Donohoe, A., Marshall, J., Ferreira, D. and Mcgee, D. 2013. The relationship between ITCZ location and cross-equatorial atmospheric heat transport: From the seasonal cycle to the Last Glacial Maximum. *Journal of Climate* 26(11): 3597-3618.

Douglas, P.M., Demarest, A.A., Brenner, M. and Canuto, M.A. 2016. Impacts of climate change on the collapse of lowland Maya civilization. *Annual Review of Earth and Planetary Sciences* 44: 613-645.

Dubois, N., Saulnier-Talbot, É., Mills, K., Gell, P., Battarbee, R., Bennion, H., Chawchai, S., Dong, X., Francus, P., Flower, R. and Gomes, D.F. 2018. First human impacts and responses of aquatic systems: A review of palaeolimnological records from around the world. *The Anthropocene Review* 5(1): 28-68.

Duerden, J.E. 1895. Discovery of aboriginal Indian remains in Jamaica. *Nature* 52(1338): 173-174.

Dull, R.A. 2007. Evidence for forest clearance, agriculture, and human-induced erosion in Precolumbian El Salvador. *Annals of the Association of American Geographers* 97(1): 127-141.

Dunning, N.P. and Beach, T. 2010. Farms and forests: Spatial and temporal perspectives on ancient Maya landscapes. In Landscapes and societies (pp. 369-389). Springer Netherlands.

Dunning, N.P., Beach, T.P. and Luzzadder-Beach, S. 2012. Kax and kol: Collapse and resilience in lowland Maya civilization. *Proceedings of the National Academy of Sciences* 109(10): 3652-3657.

Ehrhardt-Martinez, K. 1998. Social determinants of deforestation in developing countries: a cross-national study. *Social Forces* 77(2): 567-586.

Elias, V.O., Simoneit, B.R., Cordeiro, R.C. and Turcq, B. 2001. Evaluating levoglucosan as an indicator of biomass burning in Carajas, Amazonia: A comparison to the charcoal record. *Geochimica et Cosmochimica Acta* 65(2): 267-272.

Elsner, J.B. 2006. Evidence in support of the climate change–Atlantic hurricane hypothesis. *Geophysical Research Letters* 33(16), L16705, doi: 10.1029/2006GL026869.

Etienne, D. and Jouffroy-Bapicot, I. 2014. Optimal counting limit for fungal spore abundance estimation using Sporormiella as a case study. *Vegetation history and Archaeobotany* 23(6): 743-749.

Evans, D., Pottier, C., Fletcher, R., Hensley, S., Tapley, I., Milne, A. and Barbetti, M. 2007. A comprehensive archaeological map of the world's largest preindustrial settlement complex at Angkor, Cambodia. *Proceedings of the National Academy of Sciences* 104(36): 14277-14282.

Evans, D.H., Fletcher, R.J., Pottier, C., Chevance, J.B., Soutif, D., Tan, B.S., Im, S., Ea, D., Tin, T., Kim, S. and Cromarty, C., 2013. Uncovering archaeological landscapes at Angkor using LIDAR. *Proceedings of the National Academy of Sciences* 110(31): 12595-12600.

Evelyn, O.B. and Camirand, R. 2003. Forest cover and deforestation in Jamaica: an analysis of forest cover estimates over time. *International Forestry Review* 5(4): 354-363.

Ewel, K., Twilley, R. and Ong, J.I.N. 1998. Different kinds of mangrove forests provide different goods and services. *Global Ecology & Biogeography Letters* 7(1): 83-94.

Eyre, L.A. 1986. Deforestation in Jamaica: its rate and implications. Department of Geology, University of the West Indies, Kingston: 29.

Eyre, L.A. 1987. Jamaica: a test case for tropical deforestation. *Ambio* 16(6): 336–343.

Eyre, L.A. 1996. The tropical rainforests of Jamaica. *Jamaica Journal* 26(1): 26–37.

Faegri, K., Kaland, P.E. and Krzywinski, K. 1989. Textbook of pollen analysis (No. Ed. 4). John Wiley & Sons Ltd.

FAO. 2007. Mangroves of North and Central America 1980-2005, Country Reports. Forest Resources Assessment Programme, Working Paper 138 Rome, p. 86.

Fitzpatrick, S.M. 2013. Seafaring capabilities in the pre-Columbian Caribbean. *Journal of Maritime Archaeology* 8(1): 101-138.

Fujisaka, S., Escobar, G. and Veneklaas, E.J. 2000. Weedy fields and forests: interactions between land use and the composition of plant communities in the Peruvian Amazon. *Agriculture, Ecosystems & Environment* 78(2): 175-186.

Furtos, N.C. 1936. Fresh-water ostracoda from Florida and North Carolina. *American Midland Naturalist* 17(2): 491-522.

Gagan, M.K., Ayliffe, L.K., Beck, J.W., Cole, J.E., Druffel, E.R.M., Dunbar, R.B. and Schrag, D.P. 2000. New views of tropical paleoclimates from corals. *Quaternary Science Reviews* 19(1): 45-64.

Gamble, D.W., Campbell, D., Allen, T.L., Barker, D., Curtis, S., McGregor, D. and Popke, J. 2010. Climate change, drought, and Jamaican agriculture: local knowledge and the climate record. *Annals of the Association of American Geographers* 100(4): 880-893.

Gamble, D.W., Parnell, D.B. and Curtis, S. 2008. Spatial variability of the Caribbean mid-summer drought and relation to north Atlantic high circulation. *International Journal of Climatology* 28(3): 343-350.

Garrick, L.D. 1986. The Black River Lower Morass: A threatened wetland in Jamaica. *Oryx* 20(3): 155-160.

Gelorini, V., Verbeken, A., van Geel, B., Cocquyt, C. and Verschuren, D. 2011. Modern non-pollen palynomorphs from East African lake sediments. *Review of Palaeobotany and Palynology* 164(3-4): 143-173.

Giannini, A., Kushnir, Y. and Cane, M.A. 2000. Interannual variability of Caribbean rainfall, ENSO, and the Atlantic Ocean. *Journal of Climate* 13(2): 297-311.

Gill, J.L., McLauchlan, K.K., Skibbe, A.M., Goring, S., Zirbel, C.R. and Williams, J.W. 2013. Linking abundances of the dung fungus *Sporormiella* to the density of bison: implications for assessing grazing by megaherbivores in palaeorecords. *Journal of Ecology* 101(5): 1125-1136.

Gill, R.B., Mayewski, P.A., Nyberg, J., Haug, G.H. and Peterson, L.C. 2007. Drought and the Maya collapse. *Ancient Mesoamerica* 18(2): 283-302.

Graham, E. 2000. Collapse, conquest and Maya survival at Lamanai, Belize. *Archaeology International* 4: 52-56.

Grimm, Eric C. 1987. CONISS: a FORTRAN 77 program for stratigraphically constrained cluster analysis by the method of incremental sum of squares. *Computers & Geosciences* 13(1): 13-35.

Grinsted, A., Moore, J.C. and Jevrejeva, S. 2013. Projected Atlantic hurricane surge threat from rising temperatures. *Proceedings of the National Academy of Sciences* 110(14): 5369-5373.

Grove, J.M. 2001. The initiation of the" Little Ice Age" in regions round the North Atlantic. *Climatic Change* 48(1): 53-82.

Guernsey, J.E. 1941. A Climatic Map of Jamaica on the Köppen System. *Bulletin of the American Meteorological Society* 22(8): 327-331.

Hall, T.C., Sealy, A.M., Stephenson, T.S., Kusunoki, S., Taylor, M.A., Chen, A.A. and Kitoh, A. 2013. Future climate of the Caribbean from a super-high-resolution atmospheric general circulation model. *Theoretical and Applied Climatology* 113(1-2): 271-287.

Harrison, R.D., Sreekar, R., Brodie, J.F., Brook, S., Luskin, M., O'Kelly, H., Rao, M., Scheffers, B. and Velho, N. 2016. Impacts of hunting on tropical forests in Southeast Asia. *Conservation Biology* 30(5): 972-981.

Hastenrath, S. and Polzin, D. 2013. Climatic variations in Central America and the Caribbean. *International Journal of Climatology* 33(6): 1348-1356.

Haug, G.H., Günther, D., Peterson, L.C., Sigman, D.M., Hughen, K.A. and Aeschlimann, B. 2003. Climate and the collapse of Maya civilization. *Science* 299(5613): 1731-1735.

Haug, G.H., Hughen, K.A., Sigman, D.M., Peterson, L.C. and Röhl, U. 2001. Southward migration of the intertropical convergence zone through the Holocene. *Science* 293(5533): 1304-1308.

Heaton, T.H.E., Holmes, J.A. and Bridgwater, N.D. 1995. Carbon and oxygen isotope variations among lacustrine ostracods: implications for palaeoclimatic studies. *The Holocene* 5(4): 428-434.

Hedges, S.B. 1996. Historical biogeography of West Indian vertebrates. *Annual Review of Ecology and Systematics* 27(1): 163-196.

Heiri, O., Lotter, A.F. and Lemcke, G. 2001. Loss on ignition as a method for estimating organic and carbonate content in sediments: reproducibility and comparability of results. *Journal of Paleolimnology* 25(1): 101-110.

Hendrickson, M. 2010. Historic routes to Angkor: development of the Khmer road system (ninth to thirteenth centuries AD) in mainland Southeast Asia. *Antiquity* 84(324): 480-496.

Henry, C.S. 2018. Late pre-contact era Taíno subsistence economy and diet: Zooarchaeological perspectives from Maima (Doctoral dissertation, Environment: Department of Archaeology).

Higman, B.W. 2001. Jamaica surveyed: plantation maps and plans of the eighteenth and nineteenth centuries. University of West Indies Press.

Higuera-Gundy, A., Brenner, M., Hodell, D.A., Curtis, J.H., Leyden, B.W. and Binford, M.W. 1999. A 10,300 14 C yr record of climate and vegetation change from Haiti. *Quaternary Research* 52(2): 159-170.

Higuera, P.E., Brubaker, L.B., Anderson, P.M., Hu, F.S. and Brown, T.A. 2009. Vegetation mediated the impacts of postglacial climate change on fire regimes in the south-central Brooks Range, Alaska. *Ecological Monographs* 79(2): 201-219.

Higuera, P.E., Gavin, D.G., Bartlein, P.J. and Hallett, D.J. 2011. Peak detection in sediment–charcoal records: impacts of alternative data analysis methods on fire-history interpretations. *International Journal of Wildland Fire* 19(8): 996-1014.

Hodell, D.A., Curtis, J.H., Brenner, M. 1995. Possible role of climate in the collapse of Classic Maya civilization. *Nature* 375 (6530): 391–394.

Hodell, D.A., Curtis, J.H., Jones, G.A., Higuera-Gundy, A., Brenner, M., Binford, M.W. and Dorsey, K.T. 1991. Reconstruction of Caribbean climate change over the past 10,500 years. *Nature* 352(6338): 790-793.

Holmes, J.A. 1998. A late Quaternary ostracod record from Wallywash Great Pond, a Jamaican marl lake. *Journal of Paleolimnology* 19(2): 115-128.

Holmes, J.A., Street-Perrott, F.A., Ivanovich, M. and Perrott, R.A. 1995. A late Quaternary palaeolimnological record from Jamaica based on trace-element chemistry of ostracod shells. *Chemical Geology* 124(1-2): 143-160.

Hooghiemstra, H., Olijhoek, T., Hoogland, M., Prins, M., van Geel, B., Donders, T., Gosling, W. and Hofman, C. 2018. Columbus' environmental impact in the New World: Land use change in the Yaque River valley, Dominican Republic. *The Holocene* 28(11): 1818-1835.

Hughes, M.K. and Diaz, H.F. 1994. Was there a 'Medieval Warm Period', and if so, where and when?. *Climatic Change* 26(2-3): 109-142.

Hupfer, M., Hilt, S., Jørgensen, S.E., Asolekar, S.R., Kalbar, P.P., Maillacheruvu, K.Y., Abell, R., Blanch, S., Thieme, M., Geller, W. and Koschorreck, M. 2008. Lake restoration p. 79.

Hyman, T.A. 2014. Assessing the vulnerability of beach tourism and non-beach tourism to climate change: a case study from Jamaica. *Journal of Sustainable Tourism* 22(8): 1197-1215.

Iglesias, V., Yospin, G.I. and Whitlock, C. 2015. Reconstruction of fire regimes through integrated paleoecological proxy data and ecological modeling. *Frontiers in Plant Science* 5: 785.

Isaac, B.L. 1983. The Aztec" Flowery War": A Geopolitical Explanation. *Journal of Anthropological Research* 39(4): 415-432.

Jamaica Meteorological Service. 2019. 20-year Mean Temperatures (1996-2015). Web. Accessed: April 10, 2019. URL: http://metservice.gov.jm/2017/06/11/20-year-mean-temperatures-1996-2015/

Jamaica Meteorological Service. 2019. 30-year Mean Rainfall by Station (in mm). Web. Accessed: April 10, 2019. URL: http://metservice.gov.jm/30-year-mean-rainfall-by-station-in-mm/

Janzen, D. 1988. Tropical dry forests. The most endangered major tropical ecosystem. Biodiversity (ed. by E.O. Wilson), pp. 130–137. National Academy of Sciences/Smithsonian Institution, Washington DC.

Johnsen, S.J., Dahl-Jensen, D., Gundestrup, N., Steffensen, J.P., Clausen, H.B., Miller, H., Masson-Delmotte, V., Sveinbjörnsdottir, A.E. and White, J. 2001. Oxygen isotope and palaeotemperature records from six Greenland ice-core stations: Camp Century, Dye-3, GRIP, GISP2, Renland and NorthGRIP. *Journal of Quaternary Science* 16(4): 299-307.

Jones, P.D. and Mann, M.E. 2004. Climate over past millennia. *Reviews of Geophysics* 42(2).

Jury, M., Malmgren, B.A. and Winter, A. 2007. Subregional precipitation climate of the Caribbean and relationships with ENSO and NAO. *Journal of Geophysical Research: Atmospheres* 112(D16).

Kahr, B., Lovell, S. and Subramony, J.A. 1998. The progress of logwood extract. *Chirality: The Pharmacological, Biological, and Chemical Consequences of Molecular Asymmetry* 10(1-2): 66-77.

Keatings, K.W., Heaton, T.H.E. and Holmes, J.A. 2002. Carbon and oxygen isotope fractionation in non-marine ostracods: results from a 'natural culture' environment. *Geochimica et Cosmochimica acta* 66(10): 1701-1711.

Keegan, W.F., Hofman, C.L. and Ramos, R.R. eds. 2013. "The Humanization of the Insular Caribbean", In The Oxford Handbook of Caribbean Archaeology. Oxford University Press. p. 129.

Kennedy, L.M., Horn, S.P. and Orvis, K.H. 2006. A 4000-year record of fire and forest history from Valle de Bao, Cordillera Central, Dominican Republic. *Palaeogeography, Palaeoclimatology, Palaeoecology* 231(3): 279-290.

Kennett, D.J., Breitenbach, S.F., Aquino, V.V., Asmerom, Y., Awe, J., Baldini, J.U., Bartlein, P., Culleton, B.J., Ebert, C., Jazwa, C. and Macri, M.J. 2012. Development and disintegration of Maya political systems in response to climate change. *Science* 338(6108): 788-791.

Kilham, P. and Kilham, S.S. 1990. OPINION Endless summer: internal loading processes dominate nutrient cycling in tropical lakes. *Freshwater Biology* 23(2): 379-389.

Kirch, P.V. and Ellison, J. 1994. Palaeoenvironmental evidence for human colonization of remote Oceanic islands. *Antiquity* 68(259): 310-321.

Knutson, T.R., McBride, J.L., Chan, J., Emanuel, K., Holland, G., Landsea, C., Held, I., Kossin, J.P., Srivastava, A.K. and Sugi, M. 2010. Tropical cyclones and climate change. *Nature Geoscience* 3(3): 157-163.

Kozlowski, J.K.1974. Preceramic cultures of the Caribbean. Uniwertytetu Jagiellonskiego, Kraków.

Kuhar, U., Germ, M., Gaberščik, A. and Urbanič, G. 2011. Development of a River Macrophyte Index (RMI) for assessing river ecological status. *Limnologica-Ecology and Management of Inland Waters* 41(3): 235-243.

Lachniet, M.S., Asmerom, Y., Burns, S.J., Patterson, W.P., Polyak, V.J. and Seltzer, G.O. 2004. Tropical response to the 8200 yr BP cold event? Speleothem isotopes indicate a weakened early Holocene monsoon in Costa Rica. *Geology* 32(11): 957-960.

Lambert, W.J., Aharon, P. and Rodriguez, A.B. 2008. Catastrophic hurricane history revealed by organic geochemical proxies in coastal lake sediments: a case study of Lake Shelby, Alabama (USA). *Journal of Paleolimnology* 39(1): 117-131.

Landsea, C.W. 1993. A climatology of intense (or major) Atlantic hurricanes. *Monthly Weather Review* 121(6): 1703-1713.

Lane, C.S., Horn, S.P., Mora, C.I. and Orvis, K.H. 2009. Late-Holocene paleoenvironmental change at mid-elevation on the Caribbean slope of the Cordillera Central, Dominican Republic: a multi-site, multi-proxy analysis. *Quaternary Science Reviews* 28(23): 2239-2260.

Last, W.M. (Eds.), Tracking Environmental Change Using Lake Sediments. Terrestrial, Algal, & Siliceous Indicators, vol. 3. Kluwer Academic Publishers, Dordrecht: 75e97.

Laurance, W.F., Goosem, M. and Laurance, S.G. 2009. Impacts of roads and linear clearings on tropical forests. *Trends in Ecology & Evolution* 24(12): 659-669.

Laurance, W.F., Sayer, J. and Cassman, K.G. 2014. Agricultural expansion and its impacts on tropical nature. *Trends in Ecology & Evolution* 29(2): 107-116.

LeBlanc, A.R., Kennedy, L.M., Liu, K.B. and Lane, C.S. 2017. Linking hurricane landfalls, precipitation variability, fires, and vegetation response over the past millennium from

analysis of coastal lagoon sediments, southwestern Dominican Republic. *Journal of Paleolimnology* 58(2): 135-150.

Lee, S.Y., Primavera, J.H., Dahdouh-Guebas, F., McKee, K., Bosire, J.O., Cannicci, S., Diele, K., Fromard, F., Koedam, N., Marchand, C. and Mendelssohn, I. 2014. Ecological role and services of tropical mangrove ecosystems: a reassessment. *Global Ecology and Biogeography* 23(7): 726-743.

Leng, M.J. and Marshall, J.D. 2004. Palaeoclimate interpretation of stable isotope data from lake sediment archives. *Quaternary Science Reviews* 23(7): 811-831.

Lewsey, C., Cid, G. and Kruse, E. 2004. Assessing climate change impacts on coastal infrastructure in the Eastern Caribbean. *Marine Policy* 28(5): 393-409.

Li, H.C. and Ku, T.L. 1997. $\delta^{13}C$–$\delta^{18}C$ covariance as a paleohydrological indicator for closed-basin lakes. *Palaeogeography, Palaeoclimatology, Palaeoecology* 133(1-2): 69-80.

Liegel, L.H. 1991. Growth and site relationships of Pinus caribaea across the Caribbean Basin. Gen. Tech. Rep. SO-83. New Orleans, LA: US Dept of Agriculture, Forest Service, Southern Forest Experiment Station. 70 p., 83.

Lister, G.S., Kelts, K., Zao, C.K., Yu, J.Q. and Niessen, F. 1991. Lake Qinghai, China: closed-basin like levels and the oxygen isotope record for ostracoda since the latest Pleistocene. *Palaeogeography, Palaeoclimatology, Palaeoecology* 84(1-4): 141-162.

Liu, K.B. and Fearn, M.L. 2000. Reconstruction of prehistoric landfall frequencies of catastrophic hurricanes in northwestern Florida from lake sediment records. *Quaternary Research* 54(2): 238-245.

Longrich, N.R. and Olson, S.L. 2011. The bizarre wing of the Jamaican flightless ibis *Xenicibis xympithecus*: a unique vertebrate adaptation. *Proceedings of the Royal Society of London B: Biological Sciences*: p.rspb20102117.

Lotter, A.F. 2003. Multi-proxy climatic reconstructions. *Global Change in the Holocene*: 373-383.

Lozano-García, M., Caballero, M., Ortega, B., Rodríguez, A. and Sosa, S. 2007. Tracing the effects of the Little Ice Age in the tropical lowlands of eastern Mesoamerica. *Proceedings of the National Academy of Sciences* 104(41): 16200-16203.

Lozano-García, S., Caballero, M., Ortega, B., Sosa, S., Rodríguez, A. and Schaaf, P. 2010. Late Holocene palaeoecology of Lago Verde: evidence of human impact and climate

change in the northern limit of the neotropics during the late formative and classic periods. *Vegetation History and Archaeobotany* 19(3): 177-190.

Lucero, L.J. 2018. A Cosmology of Conservation in the Ancient Maya World. *Journal of Anthropological Research* 74(3): 327-359.

Lucero, L.J., Fletcher, R. and Coningham, R. 2015. From 'collapse' to urban diaspora: the transformation of low-density, dispersed agrarian urbanism. *Antiquity* 89(347): 1139-1154.

M. C. Peel, B. L. Finlayson, T. A. Mcmahon. 2007. Updated world map of the Köppen-Geiger climate classification. Hydrology and Earth System Sciences Discussions, European Geosciences Union 4 (2): 439-473. <hal-00298818>

MacPhee, R.D.E. 2009. Insulae infortunatae: establishing a chronology for Late Quaternary mammal extinctions in the West Indies. In American megafaunal extinctions at the end of the Pleistocene (pp. 169-193). *Springer Netherlands*.

Mann, M.E., Zhang, Z., Rutherford, S., Bradley, R.S., Hughes, M.K., Shindell, D., Ammann, C., Faluvegi, G. and Ni, F. 2009. Global signatures and dynamical origins of the Little Ice Age and Medieval Climate Anomaly. *Science* 326(5957): 1256-1260.

Mantsis, D.F. and Clement, A.C. 2009. Simulated variability in the mean atmospheric meridional circulation over the 20th century. *Geophysical Research Letters* 36(6).

Martin, E.R. and Schumacher, C. 2011. Modulation of Caribbean precipitation by the Madden–Julian oscillation. *Journal of Climate* 24(3): 813-824.

Maslin, M.A. and Burns, S.J. 2000. Reconstruction of the Amazon Basin effective moisture availability over the past 14,000 years. *Science* 290(5500): 2285-2287.

Masson, V., Vimeux, F., Jouzel, J., Morgan, V., Delmotte, M., Ciais, P., Hammer, C., Johnsen, S., Lipenkov, V.Y., Mosley-Thompson, E. and Petit, J.R. 2000. Holocene climate variability in Antarctica based on 11 ice-core isotopic records. *Quaternary Research* 54(3): 348-358.

Maxwell, A.L. 2004. Fire regimes in north-eastern Cambodian monsoonal forests, with a 9300-year sediment charcoal record. *Journal of Biogeography* 31(2): 225-239.

Mcandrews, J.H. 1988. Human disturbance of North American forests and grasslands: the fossil pollen record. In Vegetation history (pp. 673-697). Springer, Dordrecht.

McClenachan, L. and Cooper, A.B. 2008. Extinction rate, historical population structure and ecological role of the Caribbean monk seal. *Proceedings of the Royal Society of London B: Biological Sciences* 275(1641): 1351-1358.

McFarlane, D.A., Lundberg, J. and Fincham, A.G. 2002. A late Quaternary paleoecological record from caves of southern Jamaica, West Indies. *Journal of Cave and Karst Studies* 64(2): 117-125.

McNeil, C.L. 2012. Deforestation, agroforestry, and sustainable land management practices among the Classic period Maya. *Quaternary International* 249: 19-30.

McSweeney, C., New, M., and Lizcano, G. 2008. UNDP Climate Change Country Profile Jamaica. Oxford, UK: School of Geography and Environment, University of Oxford.

Medina-Elizalde, M. and Rohling, E.J. 2012. Collapse of Classic Maya civilization related to modest reduction in precipitation. *Science* 335(6071): 956-959.

Menon, S., Soberón, J., Li, X. and Peterson, A.T. 2010. Preliminary global assessment of terrestrial biodiversity consequences of sea-level rise mediated by climate change. *Biodiversity and Conservation* 19(6): 1599-1609.

Mickleburgh, H.L. and Pagán-Jiménez, J.R. 2012. New insights into the consumption of maize and other food plants in the pre-Columbian Caribbean from starch grains trapped in human dental calculus. *Journal of Archaeological Science* 39(7): 2468-2478.

Miles, L., Newton, A.C., DeFries, R.S., Ravilious, C., May, I., Blyth, S., Kapos, V. and Gordon, J.E. 2006. A global overview of the conservation status of tropical dry forests. *Journal of Biogeography* 33(3): 491-505.

Milner-Gulland, E.J. and Bennett, E.L. 2003. Wild meat: the bigger picture. *Trends in Ecology & Evolution* 18(7): 351-357.

Mittermeier, R.A., Myers, N., Thomsen, J.B., da Fonseca, G.A. and Olivieri, S. 1998. Biodiversity hotspots and major tropical wilderness areas: approaches to setting conservation priorities. *Conservation Biology* 12(3): 516-520.

Mittermeier, R.A., Robles Gil, P., Hoffmann, M., Pilgrim, J., Brooks, T., Mittermeier, C.G., Lamoreux, J., da Fonseca, G.A.B. 2004. Hotspots revisited: Earth's biologically richest and most endangered ecoregions. CEMEX, Mexico City, Mexico.

Montenegro, R.A. and Stephens, C. 2006. Indigenous health in Latin America and the Caribbean. *The Lancet* 367(9525): 1859-1869.

Moore, C. 1991. Cabaret: Lithic workshop sites in Haiti. *Reports of the Archaeological-Anthropological Institute of the Netherlands Antilles* 9: 922–1004.

Moore, W., Elliott, W. and Lorde, T. 2017. Climate change, Atlantic storm activity and the regional socio-economic impacts on the Caribbean. *Environment, Development and Sustainability* 19(2): 707-726.

Morgan, G.S. 1993. Quaternary land vertebrates of Jamaica. *Geological Society of America Memoirs* 182: 417-442.

Morgan, G.S. and Woods, C.A. 1986. Extinction and the zoogeography of West Indian land mammals. *Biological Journal of the Linnean Society* 28(1-2): 167-203.

Mueller, J.R., Power, M.J. and Long, C.J. 2018. Climate and human influence on late Holocene fire regimes in the British Virgin Islands. *Quaternary Research*: 1-12.

Myers, N. 1988. Threatened biotas:" hot spots" in tropical forests. *Environmentalist* 8(3): 187-208.

Myers, N., Mittermeier, R.A., Mittermeier, C. G., da Fonseca, G.A. and Kent, J. 2000. Biodiversity hotspots for conservation priorities. *Nature* 403: 853-858.

Nakagawa, T. 2007. PolyCounter ver.1.0 & Ergodex DX-1: a cheap and very ergonomic electronic counter board system. *Quanternary International*: 167-168 Supplement, 298, doi:j.quaint.2007.04.001.

National Environment and Planning Agency. 2010. Summary of Jamaica's Third National Report to the Convention on Biological Diversity, 2003-2004. *NEPA*.

Nixdorf, B. and Deneke, R. 1997. Why'very shallow 'lakes are more successful opposing reduced nutrient loads. *Hydrobiologia* 342: 269-284.

Nkemdirim, L.C. 1979. Spatial and seasonal distribution of rainfall and runoff in Jamaica. *Geographical Review*: 288-301.

Nogué, S., de Nascimento, L., Froyd, C.A., Wilmshurst, J.M., de Boer, E.J., Coffey, E.E., Whittaker, R.J., Fernández-Palacios, J.M. and Willis, K.J. 2017. Island biodiversity conservation needs palaeoecology. *Nature Ecology & Evolution* 1(7): s41559-017.

Nurse LA, McLean RF, Agard J, Briguglio LP, Duvat-Magnan V, Pelesikoti N, Tompkins E, Webb A. 2014. Small islands. In: Barros VR, Field CB, Dokken DJ, Mastrandrea MD, Mach KJ, Bilir TE, Chatterjee M, Ebi KL, Estrada YO, Genova RC, Girma B, Kissel ES, Levy AN, MacCracken S, Mastrandrea PR, White LL (eds) Climate change 2014: impacts,

adaptation, and vulnerability. Part B: regional aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, pp 1613–1654.

O'Brien, D. 2011. CARICOM: Regional Integration in a Post-Colonial World. *European Law Journal* 17(5): 630-648.

Oana, S. and Deevey, E.S. 1960. Carbon 13 in lake waters and its possible bearing on paleolimnology. *American Journal of Science* 258-A: 253-272.

Osborne, P.L. 2000. Tropical ecosystems and ecological concepts. Cambridge University Press, pp. 1-6.

Parducci, L., Bennett, K.D., Ficetola, G.F., Alsos, I.G., Suyama, Y., Wood, J.R. and Pedersen, M.W. 2017. Ancient plant DNA in lake sediments. *New Phytologist* 214(3): 924-942.

Parducci, L., Matetovici, I., Fontana, S.L., Bennett, K.D., Suyama, Y., Haile, J., Kjær, K.H., Larsen, N.K., Drouzas, A.D. and Willerslev, E. 2013. Molecular-and pollen-based vegetation analysis in lake sediments from central Scandinavia. *Molecular Ecology* 22(13): 3511-3524.

Parry, J.H. 1955. Plantation and provision ground: an historical sketch of the introduction of food crops into Jamaica. *Revista de historia de America* 39: 1-20.

Pearson, T.R., Burslem, D.F., Goeriz, R.E. and Dalling, J.W. 2003. Interactions of gap size and herbivory on establishment, growth and survival of three species of neotropical pioneer trees. *Journal of Ecology* 91(5): 785-796.

Pelaez, L.A.P., Moreno-Casasola, P. and Rosas, H.L. 2014. Hydrophyte composition of dune lakes and its relationship to land-use and water physicochemistry in Veracruz, Mexico. *Marine and Freshwater Research* 65(4): 312-326.

Pérez, L., Lorenschat, J., Brenner, M., Scharf, B. and Schwalb, A. 2010. Extant freshwater ostracodes (Crustacea: Ostracoda) from Lago Peten Itza, Guatemala. *Revista de Biología Tropical* 58(3): 871-895.

Peters, M.E. and Higuera, P.E. 2007. Quantifying the source area of macroscopic charcoal with a particle dispersal model. *Quaternary Research* 67(2): 304-310.

Peterson, L.C. and Haug, G.H. 2005. Climate and the collapse of Maya civilization: A series of multi-year droughts helped to doom an ancient culture. *American Scientist* 93(4): 322-329.

Peterson, L.C. and Haug, G.H. 2006. Variability in the mean latitude of the Atlantic Intertropical Convergence Zone as recorded by riverine input of sediments to the Cariaco Basin (Venezuela). *Palaeogeography, Palaeoclimatology, Palaeoecology* 234(1): 97-113.

Portillo-Quintero, C.A. and Sánchez-Azofeifa, G.A. 2010. Extent and conservation of tropical dry forests in the Americas. *Biological Conservation* 143(1): 144-155.

Pregill, G.K. and Olson, S.L. 1981. Zoogeography of West Indian vertebrates in relation to Pleistocene climatic cycles. *Annual Review of Ecology and Systematics* 12(1): 75-98.

Pulwarty, R.S., Nurse, L.A. and Trotz, U.O. 2010. Caribbean islands in a changing climate. *Environment* 52(6): 16-27.

R Development Core Team, 2013. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. ISBN 3-900051-07-0, URL http://www.r-project.org.

Raczka, M.F., Bush, M.B., Folcik, A.M. and McMichael, C.H. 2016. Sporormiella as a tool for detecting the presence of large herbivores in the Neotropics. *Biota Neotropica* 16(1).

Rafter TA. and Fergusson GJ. 1957. Atom bomb effect–Recent increase of carbon-14 content of the atmosphere and biosphere. *Science* 126 (3273): 557-558.

Raper, D. and Bush, M. 2009. A test of Sporormiella representation as a predictor of megaherbivore presence and abundance. *Quaternary Research* 71(3): 490-496.

Rashford, J. 1993. Arawak, Spanish and African contributions to Jamaica's settlement vegetation. *Jamaica Journal* 24(3): 17-23.

Reimer, P.J., Baillie, M.G., Bard, E., Bayliss, A., Beck, J.W., Blackwell, P.G., Ramsey, C.B., Buck, C.E., Burr, G.S., Edwards, R.L. and Friedrich, M. 2009. IntCal09 and Marine09 radiocarbon age calibration curves, 0–50,000 years cal BP. *Radiocarbon* 51(4): 1111-1150.

Renny, R. 1807. An History of Jamaica: With Observations on the Climate, Scenery, Trade, Productions, Negroes, Slave Trade, Diseases of Europeans, Customs, Manners, And Dispositions of the Inhabitants: to which is Added, an Illustration of the Advantages which are Likely to Result from the Abolition of the Slave Trade. J. Cawthorn.

Robach, F., Thiébaut, G., Trémolières, M. and Muller, S. 1996. A reference system for continental running waters: plant communities as bioindicators of increasing eutrophication in alkaline and acidic waters in north-east France. *Hydrobiologia* 340(1-3): 67-76.

Rodríguez, M. 1999. Excavations at Maruca, a Preceramic site in southern Puerto Rico. In: Winter JH (ed) *Proceedings of the Seventeenth Congress of the International Association for Caribbean Archaeology*. Molloy College, Rockville Centre, New York: 166–180.

Rosenmeier, M.F., Hodell, D.A., Brenner, M., Curtis, J.H. and Guilderson, T.P. 2002. A 4000-year lacustrine record of environmental change in the southern Maya lowlands, Peten, Guatemala. *Quaternary Research* 57(2): 183-190.

Roubik DW. and Moreno JE. 1991. Pollen and spores of Barro Colorado Island. Missouri Botanical Garden 36: 270 pp.

Rouse, I. 1992. The Tainos: rise and decline of the people who greeted Columbus. *Yale University Press*.

Royer, A. Malaizé, B., Lécuyer, C., Queffelec, A., Charlier, K., Caley, T. and Lenoble, A. 2017. A high-resolution temporal record of environmental changes in the Eastern Caribbean (Guadeloupe) from 40 to 10 ka BP. *Quaternary Science Reviews* 155: 198-212.

Russell, J.M. and Johnson, T.C. 2005. Late Holocene climate change in the North Atlantic and equatorial Africa: Millennial-scale ITCZ migration. *Geophysical Research Letters* 32(17).

Sanford Jr, R.L. and Horn, S.P. 2000. Holocene rain-forest wilderness: a neotropical perspective on humans as an exotic, invasive species. *USDA Forest Service Proceedings RMRS* 3: 1-15.

Santiago-Valentin, E. and Olmstead, R.G. 2004. Historical biogeography of Caribbean plants: introduction to current knowledge and possibilities from a phylogenetic perspective. *Taxon* 53(2): 299-319.

Santley, R. 1985. The Political Economy of the Aztec Empire. *Journal of Anthropological Research* 41(3): 327-337.

Satchell, V.M. 1990. From plots to plantations: land transactions in Jamaica, 1866–1900. Institute of Social and Economic Research, University of the West Indies, Kingston: 197.

Schoonmaker, P.K. and Foster, D.R. 1991. Some implications of paleoecology for contemporary ecology. *The Botanical Review* 57(3): 204-245.

Schreuder, L.T., Hopmans, E.C., Stuut, J.B.W., Damsté, J.S.S. and Schouten, S. 2018. Transport and deposition of the fire biomarker levoglucosan across the tropical North Atlantic Ocean. *Geochimica et Cosmochimica Acta* 227: 171-185.

Schüpbach, S., Kirchgeorg, T., Colombaroli, D., Beffa, G., Radaelli, M., Kehrwald, N.M. and Barbante, C. 2015. Combining charcoal sediment and molecular markers to infer a Holocene fire history in the Maya Lowlands of Petén, Guatemala. *Quaternary Science Reviews* 115: 123-131.

Schwalb, A., Burns, S.J. and Kelts, K. 1999. Holocene environments from stable isotope stratigraphy of ostracods and authigenic carbonate in Chilean Altiplano Lakes. *Palaeogeography, Palaeoclimatology, Palaeoecology* 148(1): 153-168.

Scott, D., Simpson, M.C. and Sim, R. 2012. The vulnerability of Caribbean coastal tourism to scenarios of climate change related sea level rise. *Journal of Sustainable Tourism* 20(6): 883-898.

Selvaraju, R., Trapido, P.J., Santos, N., Del Mar Polo Lacasa, M. and Hayman, A.A. 2013. Climate change and agriculture in Jamaica: Agricultural sector support analysis. FAO.

Seppä, H. and Bennett, K.D. 2003. Quaternary pollen analysis: recent progress in palaeoecology and palaeoclimatology. *Progress in Physical Geography* 27(4): 548-579.

Seto, K.C., Güneralp, B. and Hutyra, L.R. 2012. Global forecasts of urban expansion to 2030 and direct impacts on biodiversity and carbon pools. *Proceedings of the National Academy of Sciences* 109(40): 16083-16088.

Sheridan, R.B. 1989. Changing Sugar Technology and the Labour Nexus in the British Caribbean, 1750-1900, with Special Reference to Barbados and Jamaica. *New West Indian Guide* 63(1/2): 59-93.

Siegel, P.E., Jones, J.G., Pearsall, D.M., Dunning, N.P., Farrell, P., Duncan, N.A., Curtis, J.H. and Singh, S.K. 2015. Paleoenvironmental evidence for first human colonization of the eastern Caribbean. *Quaternary Science Reviews* 129: 275-295.

Sivaram, P. 2013. Pollen morphology of selected bee forage plants. *Global Journal of Bio-Science and Biotechnology* 2(01): 82-90.

Smith, M.E. and Berdan, F.F. 1992. Archaeology and the Aztec empire. *World Archaeology* 23(3): 353-367.

Smol, J.P. and Douglas, M.S. 2007. From controversy to consensus: making the case for recent climate change in the Arctic using lake sediments. *Frontiers in Ecology and the Environment* 5(9): 466-474.

Smol, J.P., Wolfe, A.P., Birks, H.J.B., Douglas, M.S., Jones, V.J., Korhola, A., Pienitz, R., Rühland, K., Sorvari, S., Antoniades, D. and Brooks, S.J. 2005. Climate-driven regime shifts

in the biological communities of arctic lakes. *Proceedings of the National Academy of Sciences of the United States of America* 102(12): 4397-4402.

Sobel, A.H., Camargo, S.J., Hall, T.M., Lee, C.Y., Tippett, M.K. and Wing, A.A. 2016. Human influence on tropical cyclone intensity. *Science* 353(6296): 242-246.

Soto-Centeno, J.A. and Steadman, D.W. 2015. Fossils reject climate change as the cause of extinction of Caribbean bats. *Scientific Reports* 5: 7971.

Spencer, J.D., Brunelle, A. and Hepola, T. 2017. Using Paleoecology to Inform Land Management as Climates Change: An Example from an Oak Savanna Ecosystem. *Environmental Management* 60(6): 1090-1100.

Steadman, D.W., Martin, P.S., MacPhee, R.D., Jull, A.T., McDonald, H.G., Woods, C.A., Iturralde-Vinent, M. and Hodgins, G.W. 2005. Asynchronous extinction of late Quaternary sloths on continents and islands. *Proceedings of the National Academy of Sciences of the United States of America* 102(33): 11763-11768.

Steadman, D.W., Pregill, G.K. and Olson, S.L. 1984. Fossil vertebrates from Antigua, Lesser Antilles: evidence for late Holocene human-caused extinctions in the West Indies. *Proceedings of the National Academy of Sciences* 81(14): 4448-4451.

Stivrins, N., Soininen, J., Amon, L., Fontana, S.L., Gryguc, G., Heikkilä, M., Heiri, O., Kisielienė, D., Reitalu, T., Stančikaitė, M. and Veski, S. 2016. Biotic turnover rates during the Pleistocene-Holocene transition. *Quaternary Science Reviews* 151: 100-110.

Stouffer, R.J., Yin, J., Gregory, J.M., Dixon, K.W., Spelman, M.J., Hurlin, W., Weaver, A.J., Eby, M., Flato, G.M., Hasumi, H. and Hu, A. 2006. Investigating the causes of the response of the thermohaline circulation to past and future climate changes. *Journal of Climate* 19(8): 1365-1387.

Street-Perrott, F.A., Hales, P.E., Perrott, R.A., Fontes, J.C., Switsur, V.R. and Pearson, A. 1993. Late Quaternary palaeolimnology of a tropical marl lake: Wallywash Great Pond, Jamaica. *Journal of Paleolimnology* 9(1): 3-22.

Stuiver, M. and Quay, P.D. 1980. Changes in atmospheric carbon-14 attributed to a variable sun. *Science* 207(4426): 11-19.

Sugita, S. 1994. Pollen representation of vegetation in Quaternary sediments: theory and method in patchy vegetation. *Journal of Ecology*: 881-897.

Taylor, M.A., Enfield, D.B. and Chen, A.A. 2002. Influence of the tropical Atlantic versus the tropical Pacific on Caribbean rainfall. *Journal of Geophysical Research: Oceans* 107(C9).

Taylor, M.A., Stephenson, T.S., Chen, A.A. and Stephenson, K.A. 2012. Climate change and the Caribbean: Review and response. *Caribbean Studies* 40(2): 169-200.

Tewksbury, J.J., Huey, R.B. and Deutsch, C.A. 2003. Putting the Heat on Tropical Animals. *Science* 301: 100.

The World Bank. 2017. "Jamaica". URL: https://data.worldbank.org/country/jamaica. Date accessed: April 10, 2019.

Thompson, J.E.S. 1974. Maya astronomy. *Philosophical Transactions of the Royal Society of London A: Mathematical, Physical and Engineering Sciences* 276(1257): 83-98.

Thompson, L.G., Mosley-Thompson, E. and Henderson, K.A. 2000. Ice-core palaeoclimate records in tropical South America since the Last Glacial Maximum. *Journal of Quaternary Science* 15(4): 377-394.

Thompson, R., Battarbee, R.W., O'sullivan, P.E. and Oldfield, F. 1975. Magnetic susceptibility of lake sediments. *Limnology and Oceanography* 20(5): 687-698.

Tole, L. 2002. An estimate of forest cover extent and change in Jamaica using Landsat MSS data. *International Journal of Remote Sensing* 23(1): 91-106.

Turner, B.L. and Sabloff, J.A. 2012. Classic Period collapse of the Central Maya Lowlands: Insights about human–environment relationships for sustainability. *Proceedings of the National Academy of Sciences* 109(35): 13908-13914.

US Army Corps of Engineers. 2001. Water Resources Assessment of Jamaica. US Southern Command Mobile District and Topographic Engineering Center.

Uyarra, M.C., Cote, I.M., Gill, J.A., Tinch, R.R., Viner, D. and Watkinson, A.R. 2005. Island-specific preferences of tourists for environmental features: implications of climate change for tourism-dependent states. *Environmental Conservation* 32(1): 11-19.

von Grafenstein, U., Erlernkeuser, H. and Trimborn, P. 1999. Oxygen and carbon isotopes in modern fresh-water ostracod valves: assessing vital offsets and autecological effects of interest for palaeoclimate studies. *Palaeogeography, Palaeoclimatology, Palaeoecology* 148(1): 133-152.

Wahl, D., Schreiner, T., Byrne, R. and Hansen, R. 2007. A paleoecological record from a Late Classic Maya reservoir in the north Petén. *Latin American Antiquity* 18(2): 212-222.

Walsh, K.J., McBride, J.L., Klotzbach, P.J., Balachandran, S., Camargo, S.J., Holland, G., Knutson, T.R., Kossin, J.P., Lee, T.C., Sobel, A. and Sugi, M. 2016. Tropical cyclones and climate change. *Wiley Interdisciplinary Reviews: Climate Change* 7(1): 65-89.

Waters, M.R., Giardino, J.R., Ryter, D.W. and Parrent, J.M. 1993. Geoarchaeological investigations of St. Ann's Bay, Jamaica: the search for the Columbus Caravels and an assessment of 1000 years of human land use. *Geoarchaeology* 8(4): 259-279.

Webster, D. 2000. The not so peaceful civilization: A review of Maya war. *Journal of World Prehistory* 14(1): 65-119.

Werner, L. 1992. Cultivating the secrets of Aztec gardens. *Americas* 44: 6–16.

Wetzel, F.T., Kissling, W.D., Beissmann, H. and Penn, D.J. 2012. Future climate change driven sea-level rise: secondary consequences from human displacement for island biodiversity. *Global Change Biology* 18(9): 2707-2719.

Whitlock, C. and Larsen, C. 2001. Charcoal as a fire proxy. In: Smol, J.P., Birks, H.J.B.,

Whitlock, C., Colombaroli, D., Conedera, M. and Tinner, W. 2017. Land-use history as a guide for forest conservation and management. *Conservation Biology*. doi: 10.1111/cobi.12960.

Wilkinson, R.L. 1994. Yellow fever: Ecology, epidemiology, and role in the collapse of the Classic lowland Maya civilization. *Medical Anthropology* 16(1-4): 269-294.

Willard, D.A., Bernhardt, C.E., Weimer, L., Cooper, S.R., Gamez, D. and Jensen, J. 2004. Atlas of pollen and spores of the Florida Everglades. *Palynology* 28(1): 175-227.

Williams, J.W. and Jackson, S.T. 2007. Novel climates, no-analog communities, and ecological surprises. *Frontiers in Ecology and the Environment* 5(9): 475-482.

Williams, J.W., Jackson, S.T. and Kutzbach, J.E. 2007. Projected distributions of novel and disappearing climates by 2100 AD. *Proceedings of the National Academy of Sciences* 104(14): 5738-5742.

Wing, E.S. 2008. Pets and camp followers in the West Indies. In Case studies in environmental archaeology (pp. 405-425). Springer, New York, NY.

Wingard, G.L., Bernhardt, C.E. and Wachnicka, A. 2017. The role of paleoecology in restoration and resource management—The past as a guide to future decision-making: Review

and example from the Greater Everglades Ecosystem, USA. *Frontiers in Ecology and Evolution* 5: 11. doi: 10.3389/fevo.

Wood, J.R., Wilmshurst, J.M., Turney, C.S. and Fogwill, C.J. 2016. Palaeoecological signatures of vegetation change induced by herbivory regime shifts on subantarctic Enderby Island. *Quaternary Science Reviews* 134: 51-58.

Woodward, R.P. 2006. Medieval legacies: the industrial archaeology of an early sixteenth century sugar mill at Sevilla la Nueva, Jamaica. Doctoral dissertation, Department of Archaeology-Simon Fraser University.

Wu, L., Li, C., Yang, C. and Xie, S.P. 2008. Global teleconnections in response to a shutdown of the Atlantic meridional overturning circulation. *Journal of Climate* 21(12): 3002-3019.

Wu, X., Liang, X.Z. and Zhang, G.J. 2003. Seasonal migration of ITCZ precipitation across the equator: Why can't GCMs simulate it?. *Geophysical Research Letters* 30(15).

Yadava, M.G. and Ramesh, R. 2005. Monsoon reconstruction from radiocarbon dated tropical Indian speleothems. *The Holocene* 15(1): 48-59.

Yamamoto, L. and Esteban, M. 2017. Migration as an Adaptation Strategy for Atoll Island States. *International Migration* 55(2): 144-158.

Zolitschka, B., Francus, P., Ojala, A.E. and Schimmelmann, A. 2015. Varves in lake sediments–a review. *Quaternary Science Reviews* 117: 1-41.

BIOGRAPHY OF THE AUTHOR

Mario Williams was born in Jamaica in 1992 to the parents of Godfrey and Camille Williams. The son of two high school teacher-coaches, M. Williams grew up fascinated with reading, playing soccer, and exploring the outdoors. M. Williams would often attend field trips with his father's biology class, where his interest in the natural world deepened. A standout student-athlete at Glenmuir High School in May Pen, Jamaica, M. Williams earned a scholarship to attend the Hotchkiss School in Lakeville, Connecticut. M. Williams immersed himself in his new environment and excelled as the president of the Black and Hispanic Student Alliance and captain of the varsity soccer team his senior year. After graduating from the Hotchkiss School in 2012, M. Williams attended Franklin & Marshall College in Lancaster, Pennsylvania. M. Williams played varsity soccer for two years and was an active member of the campus community. M. Williams conducted three different student research projects at Franklin & Marshall College, with his senior project enabling him to travel to the Gulf of Mexico to study the historical ecology of marine bivalves. M. Williams earned a B.A. in Environmental Science from Franklin & Marshall College in 2016 and received the Environmental Science award. M. Williams returned to the Hotchkiss School during the summer of 2016 to work as a Resident Teaching Fellow in Environmental Science in the Summer Portals Program. M. Williams started his academic career at the University of Maine in fall 2016. He worked as a teaching assistant in the School of Biology & Ecology and taught Human Anatomy, Vertebrate Biology and Introductory Biology. He is a candidate for the Master of Science degree in Ecology and Environmental Sciences from the University of Maine in May 2019.